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Understanding Russia's Uranium Enrichment Complex

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Over a period of 50 years, the Soviet Union (and now Russia) has developed a highly-efficient centrifuge technology and a large R&D and industrial complex to produce enriched uranium for nuclear weapons (in the past) and nuclear reactors. The enrichment complex is a crown jewel of the Russian nuclear complex and will remain significant for Russia's economy. Because of its role in the 1993 U.S.-Russian HEU agreement, global nuclear markets, and efforts to control the spread of centrifuge enrichment technology, the Russian enrichment enterprise is also of significant importance to international security.

INTRODUCTION

Russia's uranium enrichment industry was established in the late 1940s to produce highly-enriched uranium (HEU) for the Soviet nuclear weapon program. In the 1950s–1960s, it also began manufacturing uranium for naval propulsion, research, and power reactors. The production of HEU for weapons stopped in the late 1980s and the enrichment facilities currently operate to meet domestic and export requirements for enriched uranium and isotope separation services.

Russia's uranium enrichment enterprise is controlled by the Ministry of Atomic Energy (Minatom) and comprises four large enrichment complexes: the Urals Electrochemical Combine (UEKhK) in Novouralsk, the Electrochemical Plant (EKhZ) in Zelenogorsk, the Siberian Chemical Combine (SKhK) in Seversk, and the Angarsk Electrolysis and Chemical Plant (AEKhK) in Angarsk, Irkutsk region.[1] All four were originally established as gaseous

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diffusion facilities. At present, they utilize the highly-efficient centrifuge isotope separation technology which enables them to produce enriched uranium and services at a very low cost. The SKhK and AEKhK also operate industrial-scale UF6 production plants that supply the enrichment facilities with feed material. The primary enrichment facilities are supported by an array of R&D and manufacturing facilities, many of which are outside of the Minatom system (see Table 1).

The enrichment sector is of critical importance to Minatom and the Russian nuclear industry. Hard currency revenues from its export operations were pivotal to Minatom's survival during the post-Soviet economic and social crisis of the 1990s, the time of collapse of many other Soviet industries. Enrichment business will remain at the core of Minatom's cash-earning activities. As an element of Minatom's fuel cycle complex, the enrichment enterprise is important to the domestic nuclear power program and Russia's exports of nuclear power technologies to foreign countries.

Russia's enrichment industry and technologies are also important from the international security standpoint. The enrichment plants, for example, are central to the implementation of the 1993 U.S.-Russian HEU agreement, perhaps the most important nonproliferation, arms control and nuclear transparency initiative between the two countries after the end of the Cold War. There is, however, also a real danger that Russia could become a source of enrichment technology, knowledge and equipment for proliferating countries.

An assessment of proliferation risks and opportunities requires better understanding of the Russian enrichment complex and technologies, including their history, current state, and future directions. This article seeks to address some of these topics.

CENTRIFUGE DEVELOPMENT AND PRODUCTION[2]

Research on the use of centrifuge methods for isotope separation in Russia was started in the mid-1930s by Fritz Lange, an escapee from Hitler's Germany. A more concerted effort was undertaken in the late 1940s–early 1950s by a group of German and Soviet scientists, led by Prof. Max Steenbeck. The critical breakthrough was made in early 1952, when Russian experts proposed a concept of a short subcritical centrifuge, that incorporated elements common to most of today's gaseous centrifuges: a thin needle bottom bearing and magnetic top bearing, stationary scoops for gas removal, and a housing, which also serves as a molecular pump.[3] The new centrifuge became a prototype for a line of industrially-manufactured centrifuges that eventually encompassed eight generations of subcritical machines (for a generalized timeline of these

Table 1: Russia's centrifuge R&D and production complex.

Facility (location)	**R&D and/or equipment manufacturing function**
Primary uranium enrichment facilities	
UEKhK (Novouralsk)	UEKhK accounts for 49% of Russia's total enrichment capacity (estimated 9.8 million SWU/y).
EkhZ (Zelenogorsk)	EkhZ accounts for 29% of Russia's total enrichment capacity (estimated 5.8 million SWU/y).
SKhK (Seversk)	SKhK accounts for 14% of Russia's total enrichment capacity (estimated 2.8 million SWU/y). It also operates an UF6 plant.
AEKhK (Angarsk)	AEKhK accounts for 8% of Russia's total enrichment capacity (estimated 1.6 million SWU/y). It also operates an UF6 plant.
Centrifuge R&D complex	
Central Design Bureau of Machine-Building (TsKBM, St. Petersburg) TsKBM's centrifuge technology section is known as Centrotech-EKhZ	Minatom's lead centrifuge designer. TsKBM designed first six generations of centrifuges and related equipment. It conducts a full R&D cycle, manufactures pilot centrifuges, and produces a variety of stable isotopes for medical and industrial purposes. The TsKBM also produces turbo-molecular pumps and other deep-vacuum systems used in isotope separation applications.
Design Bureau OKB GAZ (Nizhni Novgorod)	OKB GAZ is one of three primary centrifuge designers.
R&D and pilot units of primary enrichment facilities (Novouralsk, Seversk, Zelenogorsk, Angarsk)	UEKhK is one of three primary centrifuge designers. Other facilities also participate in centrifuge R&D and testing.
Institute of Aviation Motors (VIAM, Moscow)	VIAM develops structural materials for gaseous centrifuges
Kurchatov Institute's Institute of Molecular Physics (KI IMP, Moscow)	KI IMP works on advanced centrifuge designs and chemistry aspects of isotope separation.
Institute of Chemical Technologies (VNIIKhT, Moscow)	VNIIKhT is a center of expertise on UF6 chemistry and processing technologies.
Institute of Energy Technologies (VNIPIET, St. Petersburg)	VNIPIET is a designer of centrifuge enrichment facilities, auxiliary equipment, and instrumentation and control (I&C) systems.
Institute of Chemical Machine-Building (SverdNIIKhimMash, Yekaterinburg)	SverdlBIIKhimMash is a fuel cycle equipment designer.
Centrifuge equipment production complex	
Production Association "Precision Machines" (VPO Tochmash, Vladimir)	VPO Tochmash is one of two current primary centrifuge manufacturers.
Dyagterev Plant (Kovrov)	Dyagterev Plant is one of two current primary centrifuge manufacturers.
GAZ (probably a code name for the the Nizhegorodski Machine-Building Plant, Nizhnii Novgorod)	GAZ is a former primary centrifuge producer.
UEKhK (Novouralsk)	UEKhK is the primary producer of automatic and I&C equipment (sensors, valves, pumps, ets.).

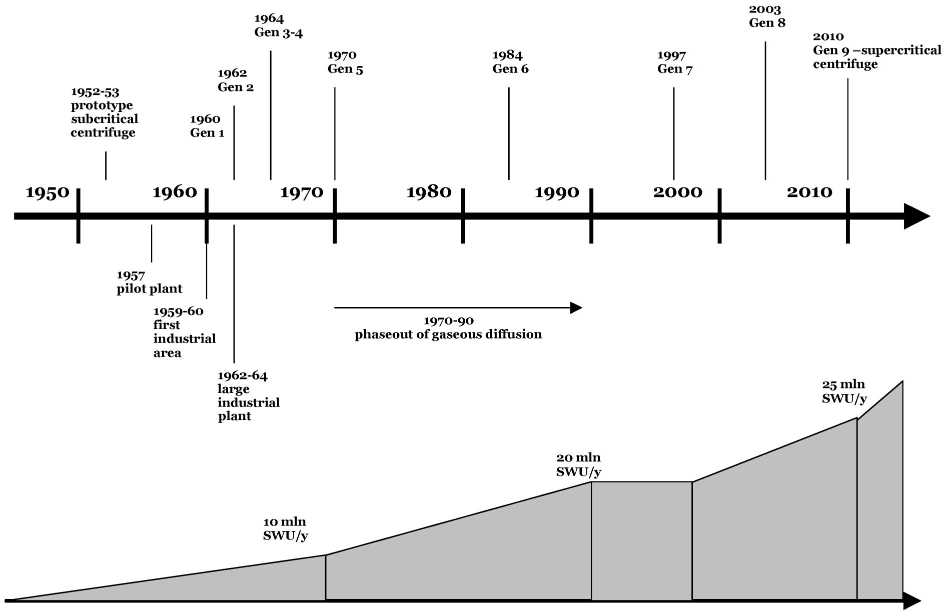


Figure 1: Notional timeline for centrifuge development and enrichment capacity growth.

developments see Figure 1). Subcritical centrifuges have become the technology of choice for uranium enrichment in the Soviet Union, as it was judged that the Soviet machinery industry was best suited for volume-production of relatively simple, but high-quality and reliable items.[4]

The industrial application of centrifuge technology began in the mid- to late 1950s. In October 1955, the Soviet government resolved to build in Novouralsk a 2,435-centrifuge pilot plant to assess the reliability and performance of the centrifuge and instrumentation and control (I&C) systems. The pilot plant was followed by an industrial facility, which was established in an area inside one of the gaseous-diffusion buildings in Novouralsk and equipped with first-generation (Gen 1) centrifuges. Based on this initial experience, on August 22, 1960, the Soviet government resolved to build in Novouralsk a large-scale centrifuge facility, which was brought into operation in three phases from 1962 to 1964. It employed centrifuges of the second and third generations, which, for the first time, were installed in multiple layers.[5] Subsequently, this arrangement allowed Soviet specialists to install a very large number of centrifuges inside the halls of the former gaseous diffusion plants.

During the 1960s–1970s, the nuclear complex conducted further centrifuge R&D, reliability assessment of centrifuges of the second, third, and fourth generations, and test-stand operation of Gen 5 centrifuges.[6] This work involved optimization of centrifuge geometry and increase in rotational speed, which, in turn, required stronger materials to manufacture centrifuge rotors. In the 1970s, the Soviet nuclear complex began modernizing all four primary enrichment facilities to finalize the transition from the gaseous diffusion to centrifuge technology.[7] This effort was based on Gen 5 centrifuges, which were deployed on a massive scale in 1971–1975, and Gen 6 centrifuges, the deployment of which began around 1984.

The development of the fifth and sixth generation machines allowed the enrichment complex to end the use of the gaseous diffusion technology by the late 1980s–early 1990s. As a result, the electricity consumption for enrichment operations decreased by an order of magnitude while the enrichment capacity was increased by a factor of 2–3.[8] By the late 1980s, the capacity reached the level of approximately 20 million SWU/y.[9]

By the late 1990s, the enrichment complex was equipped with approximately equal numbers of centrifuges of the fifth and sixth generations.[10] Gen 5 machines, which were installed in large numbers in the early-mid 1970s, are reaching the end of their useful life and are becoming unreliable. (The initial design life-time of the fifth generation machine was 12.5 years; the actual lifetime is under 25 years.[11]) All Gen 5 machines will have to be removed by 2010. Without replacement, the total separative capacity of the complex would decrease by 40 percent. In 1997 and 1998 respectively, Minatom initiated a new cycle of modernization at the UEKhK and EKhZ complexes by replacing Gen 5 machines with centrifuges of the seventh generation.[12]

In 1998, Russian experts began R&D to develop the 8th generation centrifuge. Its deployment is tentatively scheduled to begin in 2003–2004.[13] The replacement of Gen 5 centrifuges with Gen 7 machines would increase the complex's capacity by 2010 by 25 percent. Deployment of Gen 8 machines (also to replace Gen 5 centrifuges) would allow a capacity increase of 34 percent, to some 26–27 million SWU/y.[14]

The eighth generation centrifuge, however, will be the last subcritical model as it is expected that the potential for improvements in centrifuge design and materials will at that point have been exhausted. Future capacity expansion therefore is projected to involve supercritical machines. The plan, as it was formulated in the ministerial-level program "Modernization of the Enrichment Complex to 2010," is to pursue three design options for a supercritical machine: (a) rigid rotors connected by elastic steel bellows (sylphons), (b) a composite rotor with composite bellows, and (c) a metal-based, reinforced "rigid" rotor.[15]

The best design is to be selected in 2004 and the production of new centrifuges is to begin in 2010. The centrifuge production facilities appear to be in a position to produce supercritical centrifuges. Gen 9 machines would replace centrifuges of the sixth generation. Gen 6 machines, which were placed into operation in the mid-1980s, have a design life of 15 years but are projected to continue reliable operation for 30 years or until 2015.

In addition to the replacement of all Gen 5 centrifuges with Gen 7 and Gen 8 machines, and the development of a supercritical Gen 9 centrifuge, the program calls for modernization of support and auxiliary equipment (electrical, I&C, etc.) of the enrichment plants to increase safety and reliability. As of 2000, the program was projected to cost 36.7 billion rubles ($1.2 billion) and was to be financed from export revenues.[16]

PRODUCTION OF ENRICHED URANIUM AND ENRICHMENT SERVICES

During the Cold War, the four enrichment facilities operated as an integrated complex. The Novouralsk, Seversk, and Zelenogorsk plants produced HEU; the Angarsk facility produced LEU only, which, presumably, was fed into the HEU cascades of the other plants. The Soviet government exercised strict vertical control of the enrichment enterprise by assigning production quotas and resources, developing technical policies, and coordinating relations with suppliers, customers, and supporting institutions. The complex enjoyed generous financing.

The end of the Cold War and Russia's social and economic dislocations following the breakup of the Soviet Union in 1991 sent the nuclear industry into a deep crisis. The enrichment complex and the associated supporting industries were not an exception. In fact, their situation was in some respects worse because of the following factors:

- termination of the HEU production in 1988;
- phase out of the gaseous diffusion technology, which was accompanied by the shutdown of the associated supporting facilities (such as the gaseous diffusion filter plant at Novouralsk); and
- reduction in nuclear power requirements due to the closure of power reactors at Chernobyl, and in East Germany and Bulgaria, as well as the decisions by Finland's Loviisa and Czech Republic's Temelin power plant to buy nuclear fuel from Western fuel suppliers.

As a result, in the early 1990s, the enrichment complex was operating only at slightly over a half of its capacity.[17] The production of automatic and I&C

equipment (sensors, valves, pumps, etc.) at the Novouralsk complex decreased to 15–25 percent of its previous (late 1980s) levels.[18] The supporting organizations in open cities experienced a significant loss of personnel, deterioration of the R&D and manufacturing equipment base, and decreased levels of R&D and production.

The situation started to change gradually in the mid-1990s, when the enrichment complex began benefiting from new and unique opportunities, which are discussed in greater detail below. As a result, the Russian enrichment industry has not only survived in the post-Soviet era but has also become an important player in the international nuclear fuel market and a critical element of the Russian nuclear industry. At present, it covers approximately 40 percent of the world's enrichment requirements (including 15 percent from HEU-derived LEU), including nearly 100 percent of the requirements in former Soviet and East European countries. Indeed, large separative capacities and low production cost—possibly on the order of $20 per SWU (compared to approximately $70 per SWU in the United States)—which is made possible by the use of highly-efficient centrifuge technology, and access to low-cost electricity, materials and labor, make the Russian enrichment enterprise highly competitive.[19]

The Russian enrichment complex is believed to operate near its name-plate capacity of approximately 20 million SWU/y, which is used to perform the following principal tasks: production of enriched uranium for Russian-supplied reactors and western utilities, reenrichment of uranium tailings, and HEU downblending under the 1993 U.S.-Russian HEU agreement. The allocation of production capacities to these tasks is difficult to estimate with precision and is probably a subject to change from year to year. Minatom's official data for the year 2000 are presented in Figure 2.[20]

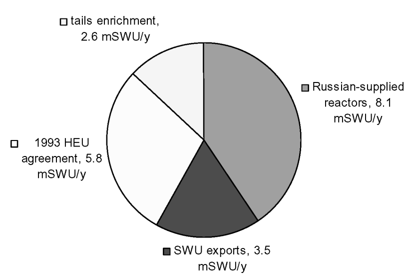


Figure 2: Minatom's enrichment capacity utilization in 2000 assuming the total capacity of 20 million SWU/y (based on: V. Shidlovsky "On the Prospects and Plans for Modernizing Enrichment Facilities," *Atompressa*, 36 (September 2000)).

LEU Production for Domestic Customers and for Exports

The Russian enrichment complex is the primary supplier of enriched uranium for the Russian-designed power reactors in the former Soviet Union and Eastern Europe.[21] According to nuclear industry analysis, the annual enrichment requirements of the former Soviet and East European power reactors could be estimated at approximately 5.3 million SWU/y.[22] However, the exact amount of enrichment work, which is used by the Russian enrichment complex to cover these requirements, is difficult to determine precisely. Two major variables include the use of domestic tails (and their assay), and the extent of the use of reprocessed uranium and the existing inventories of enriched uranium. In fact, according to Minatom data, in 2000, Russia used 40.8 percent of its capacity (approximately 8 million SWU, assuming the total capacity of 20 million SWU/y) to produce enriched uranium for Russian-designed reactors.

Russia has also become a major supplier of enrichment services to the West. In 1968, the Soviet government announced its readiness to provide enrichment services for exports.[23] The announcement was prompted by two factors. First, in the mid-1960s, the requirements for new HEU production for weapons began to decline. Second, at the same time, the enrichment capacity continued to increase due to the deployment of the centrifuge technology. The Soviet decision to enter the enrichment market coincided with the near-term capacity shortfall experienced by the U.S. enrichment enterprise (operated at that time by the U.S. Atomic Energy Commission), which was a monopoly supplier in the Western World. In 1974, the AEC temporarily closed its order books to new business, prompting the formation of new enrichment companies in Europe (Eurodif and Urenco) as well as increasing the appeal of the Soviet offer.

The Soviet Union entered the market in 1971 by signing a contract with France. The enrichment task was assigned to the Novouralsk combine which, for many years, became the principal site for export operations. The construction of the “Chelnok” (Shuttle) complex to transfer liquefied LEU UF6 into western 30B-type containers enabled the Novouralsk complex to make its first delivery under the French contract in 1973. (Similar units have subsequently been constructed at the other three sites as well.)

Enrichment exports continued to grow in the 1980s and 1990s. In addition to using customer-supplied feed material, Russia began selling enriched uranium produced from domestic uranium. The enrichment plant in Seversk started enriching reprocessed uranium for France’s Cogema. New contracts were signed with utilities in Western Europe, South Africa, South Korea, and other countries. The level of exports increased from 1.3 million SWU/y in the early 1990s to an estimated 3.5 million SWU/y in 2002. (According to Russian data, 17.4 percent of the complex's capacity, corresponding to 3.48 million SWU, was used for these purposes in 2000.)

In the future, Russia would like to increase enrichment exports to nuclear utilities in Western Europe and in the Far East. It also would like to sell enrichment services to U.S. utilities (in addition to selling HEU-derived LEU). Finally, it hopes to supply enriched uranium for Russian-designed reactors under construction in India, Iran, and China.

Despite reliability and low prices offered by Minatom a significant new near-term growth of exports is unlikely because of the competition from other major enrichers, restrictions imposed by the Euratom Procurement Agency's security of supply policy, and continued trade restrictions in the United States.[24]

In the future, however, the Russian enrichment enterprise, with its large, low cost production capacities, could play a major role in ensuring security of enrichment supply. The security of nuclear fuel supply is of strategic significance to the United States, Europe and East Asia, which rely heavily on nuclear power for energy production. The security of supply involves assurances that fresh fuel can be delivered to nuclear reactors on schedule and at reasonable prices. The enrichment industry is of special importance because enrichment accounts for a significant portion of nuclear fuel cost.

The actual world enrichment capacity today is fairly close to demand (40 versus 37 million SWU/y).[25] Much of the global demand is covered by four major producers: the U.S. Enrichment Corporation (USEC), Urenco, Eurodiff, and Minatom. A problem with one of these, such as a major accident, could result in a significant fuel supply disruption. Supply diversification, the ability of enrichment facilities to ramp up production, and the availability of stockpiles could mitigate this risk.

Of the four primary enrichment providers, Minatom has the largest capacity (about half of the total). Minatom's production operations are spread among four sites (one of which—in the Novouralsk—is composed of several separate enrichment modules) so that an accident at one facility would not cause significant supply interruption. In addition, Minatom's large production capacities and its access to HEU could be used to build up a strategic reserve. The United States and Russia have already agreed to use 15 t HEU (in addition to 500 t HEU to be downblended under the 1993 agreement, see below) to establish such a strategic stockpile. However, the U.S. Congress refused to provide implementation funds in the FY 2004 budget.[26]

1993 U.S.-Russian HEU Agreement

The downblending of HEU from dismantled weapons into LEU for deliveries to the United States has become a core activity of the Russian enrichment complex, and an important source of revenues for Minatom. The original proposal for the U.S. government to buy Russian bomb-grade uranium from dismantled nuclear weapons was put forward in October 1991 by Thomas Neff, a physicist at MIT. Formal negotiations commenced in the summer of 1992, and, on February 18, 1993, the governments of the United States and Russia signed an umbrella agreement outlining the purpose and the scope of the U.S.-Russian HEU agreement. According to the agreement, the United States is to purchase at least 500 t of HEU recovered from Russian weapons over the period of 20 years. The material is to be converted into low-enriched uranium fuel and sold to commercial nuclear power plants. The principal goal of the agreement is to "arrange the safe and prompt disposition for peaceful purposes of highly enriched uranium resulting from the reduction of nuclear weapons."[27]

Following the signing of the umbrella agreement, the U.S. and Russian governments designated the executive agents: the United States Enrichment Corporation (USEC, at that time a quasi-government entity; today, USEC is a private company), and Minatom's Tenex. The parties also began to negotiate an initial implementing contract and a transparency agreement, outlining details of implementation of the government-to-government agreement. The rest of 1993 and most of 1994 were spent negotiating these two documents and resolving a host of institutional, economic, political, and technical issues.

As Minatom and its facilities started in parallel to develop the technology and infrastructure to downblend HEU from weapons to LEU for power reactors, a technical problem emerged. It was determined that Russian HEU, much of it produced from reprocessed uranium from the plutonium-production program, was contaminated with minor actinides and chemical impurities, representing a health safety and quality problem, and it was strictly controlled by international standards.[28] Unwanted reactor-born isotopes uranium-232 and uranium-236, as well as high-concentrations of uranium-234 presented another problem.[29]

The solution proposed by Minatom experts was to bring down the concentration of impurities by radiochemical processing of HEU and by the use of a 1.5-percent uranium blend-stock that was produced by reenriching U-234-depleted uranium tails.[30] (Blending HEU with uranium of higher levels of enrichment yields larger quantities of the final product, and, in this way, increases the dilution factor.)

The initial production capability was established in Seversk (oxidation and purification) and Novouralsk (fluorination and blending) and the industrial-scale blending commenced in the fall of 1994. The first shipment of uranium under the U.S.-Russian HEU agreement took place in May 1995. The total of 156 t LEU (resulting from 6.1 t HEU) was delivered in 1995 to USEC. In 1996, the level of downblending was increased to 12 t HEU. In 1997, the parties negotiated a five-year contract according to which, 18 t HEU were to be downblended and delivered to USEC in 1997, 24 t in 1998, and 30 t per year thereafter. The USEC-Tenex contract was extended in 2002 to cover uranium deliveries (at a rate of 30 t HEU/y) to 2013 for the balance of the agreement.[31]

The production infrastructure expanded as the delivery schedules accelerated. In 1996, new fluorination and downblending facilities were commissioned in Zelenogorsk and Seversk. In 1997, trial operations to oxidize and purify HEU metal began in Ozersk, and the facility reached its capacity of 15 t HEU per year (presumably as in Seversk) in 1998. As of 1998, approximately 8,000 personnel were involved in the HEU downblending operations.[32]

At present the HEU-downblending related activities take place at each of the four enrichment sites as well as the Mayak complex in Ozersk (see Appendix: HEU Downblending Technology and Transparency Measures). The chemical and metallurgical plants in Ozersk and Seversk, originally built to manufacture HEU and plutonium components of nuclear warheads, conduct mechanical shearing and thermal oxidation of HEU metal components. Fluorination of HEU oxide powder is carried out in Zelenogorsk (presumably from Ozersk material) and Seversk. HEU downblending takes place in Novouralsk, Zelenogorsk, and Seversk. Each of the four enrichment facilities also produce the 1.5-percent enriched feedstock.

Blendstock production
8,555 t 0.25% DU + 5.34 million SWU $\rightarrow$ 916.6 t 1.5% LEU
(at 0.1% tails assay)

HEU downblending and content
30 t 93% HEU + 916.6 t 1.5% LEU $\rightarrow$ 946.6 t 4.4% LEU =
5.52 million SWU + 9,000 t NatU

According to the Russian data, the HEU downblending activities account for approximately 30 (28.9 in 2000) percent of the enrichment work in Russia or approximately 5.78 million SWU per year. (Assuming the feed and tails assays of 0.25 and 0.1 percent, respectively, the complex would have to produce approximately 5.34 million SWU/y. The discrepancy, perhaps, is due to the use of feed material with U-235 contents below 0.25 percent. Remarkably, the HEU disposition process apparently consumes more enrichment work than what it would take to make the same amount of LEU from natural uranium.) The amount of enrichment work required to support the HEU disposition is projected to remain at this level until the agreement's completion in 2013.

The HEU agreement has been perhaps the single most important bilateral nonproliferation initiative after the Cold War. The disposition of 500 t HEU—the agreement's ultimate objective—will be a significant nonproliferation achievement. (Although in the near-term, processing and transportation of large amounts of HEU create additional risk of material theft and diversion.) The HEU deal has already produced important nonproliferation benefits. Most importantly, it is a source of stable and predictable revenues for the Russian nuclear complex.[33] The HEU revenues played a critical role in preventing the collapse of the nuclear complex in the mid-1990s (which would be a major security disaster). They, along with other enrichment revenues, remain important for supporting the social stability of the Minatom complex, Russia's internal efforts to downsize the nuclear weapon production infrastructure, and programs to enhance nuclear material protection, control, and accounting. U.S. measures to confirm the HEU origin of downblended uranium have been highly successful and are an important precedent in the area of U.S.-Russian nuclear transparency (see Appendix).

The United States and Russia should explore extending the agreement beyond the currently agreed-upon 500 t HEU, the disposition of which is projected to end in 2013. Additional quantities of HEU, targeted by a new agreement, could possibly be in the range of 200–500 t HEU. (Some market analysts are pessimistic about such follow-on agreement because of apparent shortages of the blendstock and Russia's own uranium needs.[34]) Russia's agreement to declare excess and dispose of such large quantities of HEU might require reciprocal arrangements on the part of the United States. It might also require the two countries to exchange HEU stockpile data. Finally, an extension of the HEU agreement would likely require bilateral arrangements to verify nonproduction of new HEU, to ensure that neither Russia nor the United States replace downblended HEU with new-production material.

Reenrichment of Depleted Uranium Tails

Minatom's ability to reenrich tailings is based on the low cost of production and large excess enrichment capacities. Tails reenrichment for Minatom, however, is more than an opportunity to use its underutilized enrichment capacity. Minatom experts view it as a strategic source of uranium, which is particularly significant because of the loss of the Soviet uranium production operations in Central Asia and Ukraine and the projected decline in productivity of the existing uranium mines in Russia. Tails reenrichment is also critical to the HEU downblending activities under the 1993 HEU agreement.

Reenrichment of uranium tailings from past enrichment operations began in Russia in the early 1990s. According to Minatom's 1992 Integrated Nuclear Power Development Program for 1993–2000 and to 2010, the level of reenrichment work was to increase from 1.29 million SWU/y in 1993 to 6.44 million SWU/y in 2000 and was to remain at this level until 2010.[35] The plan was to first work through low-assay tails (0.20 and 0.24 percent U–235) and gradually move to higher-assay material. (Although it appears that as early as in 1992 Minatom was reenriching its 0.36-percent tailings.) Tailings were to be used to produce 0.7-percent (natural) uranium for exports as well as enriched uranium for Russian reactors.

The use of domestic tailings for the production of reactor fuel, however, has been subsequently deemphasized. Instead, in the mid- and late 1990s, the enrichment facilities began reenriching tails to produce the 1.5 percent blendstock for the HEU deal. Also in the late 1990s, Minatom signed tails-reenrichment contracts with Urenco and Cogema. Under these contracts, the two companies export to Russia 5,000–7,000 t depleted uranium tailings (containing 0.3–0.35 percent U-235) per year.[36] Russia returns 1,100 t 0.711% uranium; Cogema also receives 130 t uranium enriched to 3.5 percent U-235. The rest of the tailings is apparently used by Minatom to support the HEU deal.

The Urenco/Cogema arrangement is quite profitable for Minatom as it provides much needed clean tailings to produce the blendstock for the HEU deal and is a very significant source of uranium for Minatom (an estimated 3,300 t of natural uranium equivalent per year[37]). The contracts also allow Minatom to maintain production at its enrichment facilities.

According to the official Russian data, in 2000, these activities utilized 12.9 percent of Russia's enrichment capacity (2.58 million SWU). (According to estimates by western analysts, the reenrichment of tailings accounts for approximately 35 percent, corresponding to 7 million SWU/y, of the overall SWU production in Russia.[38]) Such massive use of tailings has dramatically reduced the workload of the UF6 production plants (to 10–15 percent of their capacity).[39]

The secondary tailings, resulting from the reenrichment of imported tailings, are the responsibility of Minatom. (Indeed, the primary motivation for Urenco and Cogema to enter into the reenrichment contracts with Russia is probably to get rid of the tailings.) These materials, however, represent a fairly small fraction of Minatom's own tailings (estimated to be on the order of 500,000 t). At present, the tailings are stored in steel tanks at each of the four enrichment sites and, according to Russian experts, could be stored safely for over 100 years. As of 2000, Minatom was working on a concept of disposal of its depleted uranium tailings.[40]

Reenrichment of uranium tailings (foreign and domestic) is projected to remain a major activity of the enrichment complex well after 2010 and will utilize a large portion of the planned capacity growth.

Enrichment Revenues

The enrichment business generates for Minatom several hundred million dollars annually ($728 million in revenues as of 2001).[41] The 1993 HEU agreement provides approximately $400 million (assuming that Minatom receives only 80 percent of the $450–500 million paid to the Russian government by USEC) and is the largest source of revenues (see Table 2).[42] Exports of enrichment services

Table 2: Minatom's estimated enrichment revenues.

Activity	Sales* MSWU/y	Price $/SWU	Gross Revenue $M	Production, MSWU/y	Production, Cost,** $M	Net Income $M
HEU-LEU	5.5	90	$495 \times 0.8 = 396$	5.8	116	280
SWU exports	3.5	80***	280	3.5	70	210
Tails enrichment	2.6	20	52	2.6	52	0
Exports Subtotal	11.6		728	11.9	238	490
Fuel for Russia-supplied reactors	5.3	61	325	8.1	162	163
Total	16.9		1,053	20	400	653

*Differences between the "sales" and "production" figures could reflect the differences between contractual obligations and the actual amount of work expended to produce the product. In the case of the HEU agreement, the "sales" figure is the calculated SWU content in LEU deliveries whereas the "production" figure relates to Minatom's work to produce the blendstock.
**Production cost is calculated based on the $20/SWU extimate.
***SWU spot market price in the fall 2003.

to Western Europe, East Asia, and South Africa generate approximately $300 million. These two activities presumably account for the largest share of Minatom's enrichment revenues.

Tails reenrichment for Urenco and Cogema presumably is less profitable financially. These tailings, however, are critical to the implementation of the HEU agreement and are a significant uranium resource.

The production of enriched uranium to fabricate fuel for Russian-supplied reactors is probably a less significant source of revenues for the enrichment complex. The enrichment plants transfer this uranium (as UF6) to the fuel fabrication plants managed by the Concern TVEL. Presumably, TVEL reimburses the enrichment facilities to cover the cost of production (plus modest profit) according to the government-set list of prices. TVEL's revenues from the sales of reactor fuel ($464 million in 2001) are then counted towards Minatom's budget.[43] Assuming that enrichment accounts for 70 percent of the front fuel cycle cost, the value of enrichment work performed to produce this fuel can be estimated at approximately $325 million.

CENTRIFUGE TECHNOLOGY EXPORTS

The financial crunch and desperation of the 1990s have driven Minatom to undertake projects involving direct exports of the Russian centrifuge technology. The project in China has been relatively successful. It was initiated by the December 18, 1992, government-to-government agreement "On Cooperation in the Construction on the Territory of the PRC of a Gaseous Centrifuge Plant for the Enrichment of Uranium for Nuclear Power."[44] In March 1993, the parties signed a general contract for the construction, in two phases, of a 500,000 SWU/y centrifuge plant at a site near Hanzhong in Shaan-xi Province. In November 1994, Minatom put into operation a pilot centrifuge cascade to train Chinese workers. In December 1996, the parties signed a protocol to the 1992 agreement. The protocol called for an expansion in Russia-supplied enrichment capacity in China to 1–1.5 at million SWU/y. It also was specified that the proposed increase would be implemented not by expanding the Shaan-xi plant, but by constructing a new 500,000 SWU/y plant in Lanzhou. On March 26, 1997, the first phase of the Shaan-xi plant (200,000 SWU/y) was brought into operation one year ahead of the schedule. The second phase of the Shaan-xi plant (300,000 SWU/y) became operational in August 1998. The 500,000 SWU/y Lanzhou plant was brought into operation around 2001; its capacity is expected to double in the future.[45]

IAEA SAFEGUARDS FOR RUSSIAN-BUILT CENTRIFUGE FACILITIES*

Safeguarding Russian-supplied centrifuge plants is a considerable challenge because "enrichment plants incorporating Russian gas centrifuges are designed for a much greater degree of operational flexibility than other plants . . . . In addition, flexible piping arrangements make it possible to bypass any installed [enrichment monitor] instrument." To design an appropriate monitoring regime, Russia, China and the IAEA have conducted a Tripartite Enrichment Project. The safeguards approach, developed under the project, describes three objectives for safeguards at Russia-supplied centrifuge facilities: (a) detection of HEU production, (b) detection of LEU production in excess of declared amounts/enrichments, and (c) detection of diversion of LEU, natural uranium, or depleted uranium. It calls for inspection activities inside and outside of the cascade hall. The proposed activities outside the cascade hall include:

- "examination of records and reports;
- accountancy and control of UF6 in feed, product and tails cylinders;
- verification of receipts and shipments;
- verification of declared transfers to and from sublimation/desublimation stations; and
- swipe sampling outside the cascade hall."

Safeguards activities inside the cascade hall include:

- "visual examination of equipment and area;
- swipe sampling in the cascade hall;
- special particulate sampling using installed sample filters (so-called "Koshelev Filters");
- product flow monitoring;
- continuous enrichment monitoring
- separative work monitoring; and
- application of containment and surveillance at sublimation/ desublimation stations and cascade hall entry and exit points."

*A. Panasyuk, A. Vlasov, S. Koshelev, T. Shea, D. Perricos, D. Yang, and S. Chen, "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges," IAEA-SM-367/8/02 (IAEA, 2001).

The Russian-built centrifuge plants in China, a recognized nuclear weapon state, are not a significant proliferation concern. Moreover, according to the Tripartite agreement between Russia, China, and the IAEA, these facilities are available for international monitoring. The Shaan-xi enrichment plant is, in fact, under IAEA safeguards (see Box: IAEA Safeguards for Russian-Built Centrifuge Facilities). As of 2001, the IAEA, however, was lacking the funds to design the enrichment and flow monitor to be installed on the product and tailings pipes. The Lanzhou plant is not under safeguards because of the IAEA's lack of funds and resources. Minatom also signed an agreement with the Committee for Nuclear Energy of China (CNEC) on management of confidential information and the protection of equipment as well as design and contract information.[46]

Novouralsk and Angarsk are the primary facilities involved in the construction of the Chinese plants. The project is quite profitable: as of 1995, the price of the contract (effectively the price of the Shaan-xi plant) was estimated at $150 million. Furthermore, the contract was a part of a package deal under which the Chinese agreed to buy Russian VVER-1000 reactors as well as 30 percent of fuel for the power plant which was being built in China by France.[47]

The Chinese plants utilize older (possibly fifth-generation) centrifuge technology and are intended to serve China's domestic customers only.[48] According to then Minister of Atomic Energy Victor Mikhailov, "[B]y the end of this decade [by 2000] we plan to transition our plants to a new generation of centrifuges with a factor of 1.5–2 higher in separative capacity relative to centrifuges supplied to China. This technology is 15-years old."[49] Certain sensitive equipment (not including centrifuges) is shrouded to protect design information. Even so, the technology transfer to China could have a long-term negative impact on Russia's competitiveness in the world's enrichment market. According to a Russian participant to the project, "[W]e are doing this at our own peril; but the money is good."[50]

Inspired by the contract with China, Minatom, in the early-mid-1990s, was looking to similar deals elsewhere. The proposed technology exports to Iran turned out an embarrassment for Minatom and the Russian government, however. The intention to initiate enrichment plant contract negotiations was recorded in the meeting protocol for the January 1995 visit to Tehran by then Minatom Minister Victor Mikhailov.[51] The Russian government terminated the project under pressure from the United States and after Minatom's plans were exposed to the public.

Indeed, the centrifuge technology presents a special nonproliferation problem. High separation capacities of individual centrifuges, small in-process material inventories, and low power and cooling requirements make it the technology of choice for a small clandestine enrichment facility. Because of a modular plant design and short cascade equilibrium time, centrifuge enrichment technology is also highly suitable for unauthorized HEU production at an ostensibly civilian enrichment facility. Russian-designed plants reportedly could be particularly vulnerable because of the relative ease of cascade reconfiguarion that could be achieved by valve manipulation.

There is a danger that Russia, with its tens of thousands of centrifuge experts, huge centrifuge R&D and manufacturing base, and large inventories of centrifuges, auxiliary equipment, and components, could become a source of equipment and know-how for proliferating states. (In fact, there are allegations, which have been denied by Minatom, that Russian entities, along with those from China and Pakistan, have been a major supplier to the Iranian centrifuge program.[52]) The Russian government is making an effort to strengthen its export controls. Technical support in this area is provided by St. Petersburg's Centrotech-EKhZ center, which works with Minatom's export controls laboratories at the Institute of Physics and Power Engineering (IPPE, Obninsk) and the Institute of Technical Physics (VNIITF, Snezhinsk). The Russian government also seeks to prevent unauthorized transfers of centrifuge technologies. In 2000, for example, operatives of the Federal Security Service's (FSB) regional directorate in Chelyabinsk apprehended a Chinese national as he was buying centrifuge documentation and equipment from Russian enrichment workers in the Urals.[53]

CONCLUSION

Over a period of 50 years, the Soviet Union (and now Russia) has developed a highly efficient centrifuge technology and a large R&D and industrial complex to produce enriched uranium for nuclear weapons (in the past) and nuclear reactors. The enrichment complex is a crown jewel of Minatom and will remain significant for Russia's economy. Because of its role in the 1993 HEU agreement, global nuclear markets, and efforts to control the spread of centrifuge enrichment technology, the Russian enrichment enterprise is also of significant importance to international security. Perhaps the most effective way to harness its positive potential and make it more transparent to the West as well as to arrest negative developments (such as uncontrolled centrifuge exports) is to more fully integrate the Russian enrichment complex into the Western nuclear market. Such integration could involve removal of trade barriers, strategic partnerships with primary uranium enrichers in the West, extension of HEU downblending past 2013, new transparency initiatives (such as an

HEU nonproduction initiative), and construction of internationally operated, Russian-supplied enrichment facilities in western countries. A strategic course of such integration would serve international nonproliferation and energy security interests and would facilitate the economic and political integration of Russia into the western world.

APPENDIX: HEU DOWNBLENDING TECHNOLOGY AND TRANSPARENCY MEASURES

HEU-to-LEU Downblending Technology

The downblending operations under the 1993 HEU agreement utilize the UF6 process. The principal steps in the UF6 process are the reduction in size, purification, fluorination, and blending with the UF6 blend-stock.

The principal steps of the oxidation process are as follows. Warhead components are shredded into chips and shavings and the material is sampled and analyzed. HEU shavings are oxidized in special furnaces, and the oxide is milled and sieved to produce a uniform powder. The powder is sampled, and, if the level of impurities is unacceptable, is cleaned in a solvent-extraction process. (More than one solvent-extraction cycle might be required.) Prior to transportation to a fluorination facility, pure oxide is loaded in transportation containers (approximately 6 kg per container) and weighed. Transportation containers are placed in overpacks which are sealed and secured in a railcar by heavy containment devices.

At a fluorination facility, the HEU oxide powder is received and weighed. Samples of the material are analyzed for quality. HEU oxide is fluorinated in flame reactors and condensed inside 6-liter technological vessels. Liquid UF6 is transferred to 12-liter vessels, weighed, and analyzed to determine the concentration of U-235. HEU slugs, which are formed during fluorination, are sent back to the oxidation facility to recover HEU.

The 12-liter vessels are transferred to an enrichment plant where HEU UF6 is fed into the T-pipe unit for mixing with 1.5-percent enriched UF6. After mixing, the resulting LEU UF6 product is pumped to the desublimation unit. After sampling, LEU is loaded in industry-standard 30B cylinders for shipment to the United States.

HEU Downblending Transparency

The 1993 umbrella agreement called for a transparency agreement that would "establish transparency measures to ensure that the objectives of [the]

Agreement are met." In particular, these objectives were to ensure that HEU from weapons is downblended to LEU and that this LEU product is fabricated into fuel for commercial reactors and is not recycled in the U.S. nuclear weapons program.

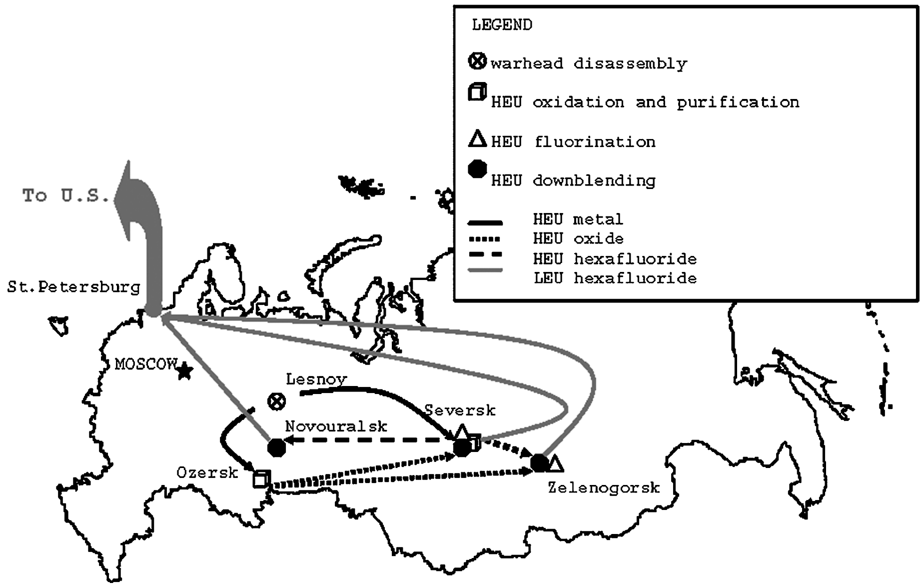
The process of establishing an effective transparency regime has been difficult. In the United States, the key questions were how to verify that (a) the material entering the downblending device is indeed HEU, and (b) that it comes from nuclear weapons and is not from non-weapons stocks. (At present, the United States is content with buying any HEU metal that is not freshly-produced.[54]) In Russia, the main practical interest seemingly was to learn intricacies of the fuel fabrication processes employed by the U.S. fuel fabricators.

After the Memorandum of Understanding and the Protocol on Transparency were signed in September 1993 and March 1994, the Transparency Review Committee (TRC) was established and met for the first time in September 1994 to negotiate specific arrangements. It was decided to give TRC one year to resolve the existing problems. If no result was achieved by that time, the level of discussions would be elevated to the political level. If no acceptable solution was found at the political level, the U.S. and Russian governments could then direct USEC and Tenex respectively not to issue or accept delivery orders.

The implementation of effective transparency measures remained essentially stalled until June 1995 when the Joint Statement on Transparency Measures was signed at the Fifth Session of the Gore-Chernomyrdin Meeting. (Many analysts believe that cash-starved Minatom accepted some of the proposed transparency measures in exchange for a $100 million advance under the HEU deal.) The Statement allowed the parties to access the facilities involved in the HEU agreement. By the fourth TRC meeting in April 1996, the parties resolved the remaining differences regarding HEU measurements and access and finalized 14 annexes to the Protocol on Transparency that provides a detailed description of the transparency regime. (The number of annexes subsequently has increased as new Russian facilities joined the HEU down-blending process.)

The principal components of the regime include familiarization visits, special monitoring visits, permanent monitors at Russia's downblending facilities and in Portsmouth, OH, and the development of new monitoring techniques. Familiarization visits served to exchange and confirm information on processing technologies and accounting procedures at a host site, and to determine specific transparency measures and requirements. Familiarization visits to U.S. and Russian facilities began in 1993.

Special monitoring visits to a particular facility take place every several months. First such visits took place in 1996. Also in 1996, permanent presence



Map: HEU to LEU flows within Russia.

offices were established in Novouralsk and Portsmouth, OH. (Permanent offices have subsequently been established at other downblending facilities in Russia as well.)

According to an expert from the Lawrence Livermore National Laboratory, during a special monitoring visit to an oxidation facility, U.S. monitors "can observe the whole oxidation procedure, from the beginning when the uranium metal is analyzed by portable gamma-ray spectrometry to confirm its weapons-grade status, through its feed into and withdrawal from oxidation process equipment, to the final analysis of the withdrawn oxides."[55] The monitors also apply tags to HEU oxide containers prior to their shipment to a downblending facility.[56]

At the downblending facilities, both special and permanent monitors "have the right to check tags and seals on containers of HEU oxide . . , inventory containers of HEU oxide and HEU hexafluoride in storage, visit the blend point and request and observe the withdrawal and analysis of samples removed from the blend point, record pressure readings to determine the flow of uranium at the blend point, and observe the application of U.S. tags and seals on orifice plates in the pipes at the blending point."[57] Both special and permanent monitors have access to material accounting data pertinent to the implementation of the HEU agreement. In addition, since 1999, the United States has installed at Russian downblending facilities nonintrusive nondestructive assay instruments. The Blend Down Monitoring System (BDMS) is installed on each of the three legs of the blending tee and measures U-235 enrichment of gaseous UF6. The system is based on the activation of the fissile stream by neutrons and subsequent detection of delayed radiation produced by fission products.

NOTES AND REFERENCES

1. In March 2004, Minatom became the Russian Federation Agency for Atomic Energy.

2. For a more detailed discussion of the Soviet/Russian centrifuge program see: Oleg Bukharin *Russia's Gaseous Centrifuge Technology and Enrichment Complex*, Program on Science and Global Security's report (Princeton, 2004).

3. In a molecular pump, a high rotational speed rotor imparts momentum to the gas molecules: the pumping action thus is achieved at a molecular level by bouncing gas molecules off the rotor and the stator. In a centrifuge, the role of a stator is played by a close-fitting spiral grooved sleeve located around the upper portion of the centrifuge rotor (which also serves as the pump's rotor). This molecular pump system evacuates all leakages of the UF6 gas to the top region of the centrifuge from where the gas is removed by an external vacuum system.

4. A high-speed rotation of a sufficiently long tube with a small diameter results in flexural (transverse) resonances. These resonances occur at critical speeds that are determined by the rotor's design and characteristics of materials it is made of (density and elasticity). A centrifuge operating at a speed below that of its first flexural resonance (a short centrifuge) is termed subcritical. A centrifuge operating at speeds above the first resonance is termed "supercritical." A supercritical rotor with a high length-to-diameter ratio could pass through several critical resonance frequencies on its way to the designed high rotational speed. Unless the rotor is carefully balanced and unless vibrations are controlled by the use of damping measures, the rotor could be destroyed while traversing these critical frequencies.

5. Vladimir Bazhenov and Yuri Zabelin, "The Creation and Development of the Centrifuge Method for Isotope Separation," *UEKhK Information Newsletter*, No. 3 (18 February 1999).

6. B. Bazhenov and Yu. Zabelin, "The Creation and Development of the Centrifuge Method for Isotope Separation," *UEKhK Information Bulletin* (18 February 1999).

7. Yu. Verbin, "Development of Chemical and Technological Facilities and Environmental Protection," *Atompressa*, 40 (November 1998).

8. V. Safutin, Yu. Verbin, and V. Tolstoi, "The Status and Perspectives of Separation Production," *Atomnaia Energiia*, vol. 89, No. 4 (October 1, 2000), 338–343.

9. Victor Mikhailov, "The Nuclear Industry in Russia," presented at The Twenty-Second International Symposium, The Uranium Institute, London, 1997 (available at: www.world-nuclear.org/sym/1997/mikhail.htm).

10. As of 2000, the Gen 5, 6, and 7 centrifuges accounted for 48, 49, and 3 percent of the total, respectively. UEKhK operated Gen 5, 6, 7 centrifuges; EKhZ operated Gen 5, 6, 7 centrifuges; SKhK operated Gen 5 and 6 centrifuges; and AEKhK operated Gen 6 centrifuges. V. Safutin, Yu. Verbin, and V. Tolstoi, "The Status and Perspectives of Separation Production," *Atomnaia Energiia*, vol. 89, No. 4 (October 1, 2000), 338–343.

11. V. Shidlovsky, "On the Prospects and Plans for Modernizing Enrichment Facilities," *Atompressa*, 36 (September 2000).

12. Ibid.

13. "To Meet Modern Requirements: Interview with Vladimir Korotkevich," available at: www.minatom.ru/presscenter/document/news/PRINT_news344.htm.

14. V. Safutin, Yu. Verbin, and V. Tolstoi, "The Status and Perspectives of Separation Production," *Atomnaia Energiia*, vol. 89, No. 4 (October 1, 2000), 338–343.

15. V. Shidlovsky, "On the Prospects and Plans for Modernizing Enrichment Facilities," *Atompressa*, 36 (September 2000).

16. V. Safutin, Yu. Verbin, and V. Tolstoi, "The Status and Perspectives of Separation Production," *Atomnaia Energiia*, vol. 89, No. 4 (October 1, 2000) 338–343.

17. For example, according to E. Mikerin, V. Bazhenov, and G. Solovyev, "Directions in the Development of Uranium Enrichment Technology," (Minatom, undated), at least 10 million SWU/y were available for exports in the early 1990s.

18. UEKhK's presentation at the workshop on downsizing of the Minatom nuclear weapons complex; Obninsk, 27–29 June 2000.

19. For an analysis of cost production see Matthew Bunn, "The Cost of Rapid Blend-Down of Russian HEU," July 11, 2001. Interestingly, at least as of 2000, neither the enrichment facilities nor Minatom knew their SWU production cost; see, V. Shidlovsky, "On the Prospects and Plans for Modernizing Enrichment Facilities," *Atompressa*, 36 (September 2000).

20. For Minatom capacity breakdown data, see, for example, V. Shidlovsky "On the Prospects and Plans for Modernizing Enrichment Facilities," *Atompressa*, 36 (September 2000).

21. A small portion of requirements is covered by western suppliers and by reprocessed uranium recovered at the Mayak complex from VVER-440 spent fuel and sweetened by medium- or highly-enriched uranium.

22. Dr. Arthur Max, Nukem, personal communication, 2003.

23. A. Novikov "30 Years of Russian Uranium Exports: Interview with A. Knutarev," *Atompressa*, 16 (2003).

24. Minatom's primary competitors and their 2002 share of the world's enrichment market are USEC (18%), Eurodif (23%), and Urenco (15%). Japan and China also seek a bigger role in the enrichment market. (Jean-Jacques Gautrot, "The Harmonious Market for Uranium Enrichment Services," presented at World Nuclear Association Annual Symposium, September 4–6, 2002, London; www.world-nuclear.org/sym/2002/pdf/gautrot.pdf.) The Euratom Procurement Agency restricts imports of enriched uranium from Russia to 25%. In 2002, Russian supplies accounted for 14% of the EU enrichment requirements. ("Euratom Releases Annual Report 2002," *The Ux Weekly* [June 9, 2003]). The United States prohibits imports of any Russian enrichment

services with the exception of those contained in HEU-derived LEU delivered under the 1993 HEU agreement.

25. Jean-Jacques Gautrot, "The Harmonious Market for Uranium Enrichment Services," presented at World Nuclear Association Annual Symposium, September 4–6, 2002, London; www.world-nuclear.org/sym/2002/pdf/gautrot.pdf.

26. Daniel Horner, "Conferees Nix Plan to Fund Downblending of More Russian HEU," *Nuclear Fuel* (10 November 2003), 1, 14.

27. "Russian-U.S. HEU Agreement," *Nuclear Fuel* (March 1, 1993).

28. Because Russian HEU was produced from reprocessed uranium it contains traces of transuranic elements (plutonium, americium, curium) and fission products. Additional amounts of americium and plutonium might have been acquired due to metal diffusion in composite HEU/plutonium warhead components. Initially (in 1994), Russian experts suggested that a reasonable level of alpha-activity (from Pu-238/239 and Np-237) for HEU-derived LEU would be 0.1 Bq/gU; the suggested limit for gamma-activity from fission products was 1.1×10^5 MeV/sec/kgU; Michael Knapik, "ASTM to Develop New Standard for Blended-Down HEU from Weapons," *Nuclear Fuel* (28 March 1994).

29. The reactor-origin isotope uranium-232 presents an occupational safety problem because it decays into bismuth-212 and tellurium-208, both high-energy gamma emitters. Uranium-236, also formed in a nuclear reactor, is a neutron poison and its presence in reactor fuel has to be compensated by higher levels of enrichment in uranium-235. Uranium-234 is a natural isotope. Its concentration in HEU is, however, relatively high due to a preferential enrichment of lighter isotopes. Because uranium-234 is a strong alpha emitter, there are restrictions on its concentration in uranium. Russia's proposal was to set the following limits for blended-down HEU: 0.002 mcgU-232/gU-235, 11,000 mcgU-234/gU-235 (the limit imposed by ASTM C 996-90 for commercial grade uranium is 10,000 mcgU-234/gU-235), and 10,000 mcgU-236/gU-235; Ibid.

30. Unless HEU is blended with uranium depleted in uranium-234 (such as uranium derived from uranium enrichment tailings) the concentration of uranium-234 in HEU-derived LEU is higher compared to LEU produced from natural uranium.

31. The contract covers only the enrichment component of the LEU product delivered to USEC. Payments for the natural uranium component contained in the LEU were a considerable problem for many years. In 2001, however, an arrangement was agreed upon under which two Western companies (Cameco and Nukem) have a first right to buy uranium. After that, USEC returns an used portion of natural uranium to Russia.

32. "Peaceful Atom in Private Hands Could Result in Economic Wars Abroad and a Full Collapse of the Industry at Home," *Rossiyskaya Gazeta* (5 June 1998), 4.

33. The revenues from the LEU sales are directed to the Russian budget (the Ministry of Finance). Minatom, the Ministry of Finance, the Ministry of the Economic Development, and other elements of the Russian government then negotiate the disbursement of the HEU revenues. Reportedly, approximately 80 percent of the revenues are returned to Minatom which, in turn, reimburses the downblending facilities in the amount of the cost of production plus 20–25 percent award. The rest of Minatom's moneys are placed into the Special Minatom Fund, which is used to cover the Ministry's overhead as well as to support defense conversion, nuclear safety and security, social security, and other industry-wide programs.

34. See for example, "Top Ten Stories of 2003," *The Ux Weekly* (22 December 2003).

35. "Integrated Nuclear Power Development Program for 1993–2000 and to 2010" (Minatom, 1992).

36. Dr. Arthur Max, Nukem, personal communication, 2003.

37. Ibid.

38. Ibid.

39. Nikolai Egorov, Vladimir Novikov, Frank Parker, and Victor Popov, (eds.), *The Radiation Legacy of the Soviet Nuclear Complex* (London: Earthscan Publications Ltd, 2000).

40. The principal participants in this project are the four enrichment facilities, the TRINITY center, the Institue of Energy Technologies (VNIPIET, St. Petersburg), and the Institute of Energy Problems. See: *Atompressa*, 44 (November 2000).

41. Oana Diaconu and Michael Maloney, "Russian Commercial Nuclear Initiatives and U.S. Nonproliferation Interests," *Nonproliferation Review* (Spring 2003): 97–112.

42. The 2002 contract between USEC and Tenex established a new, reduced SWU price. The level of payments to Russia is likely to decline considerably as a result.

43. Oana Diaconu and Michael Maloney "Russian Commercial Nuclear Initiatives and U.S. Nonproliferation Interests," *Nonproliferation Review* (Spring 2003): 97–112.

44. "Russia-PRC Nuclear Power Development Cooperation: Traditions, Real Results, Problems, and Prospects," *Atompressa*, 11 (March 1998).

45. Platts Nov. 12, 2001; *Nuclear Fuel*, May 17, 1999. ⟨www.antenna.nl/wise/uranium/eproj.html#LANZHOUCENT⟩.

46. "Russia-PRC Nuclear Power Development Cooperation: Traditions, Real Results, Problems, and Prospects," *Atompressa*, 11 (March 1998).

47. "Information," *Yaderny Kontrol*, 1 (January 1995).

48. Reportedly, Minatom is selling to China its older, overstock centrifuges. See: "Hanzhun Enrichment Facility," at ⟨http://www.nti.org/db/china/hanzhun.htm⟩.

49. Quoted in "Information," *Yaderny Kontrol*, 1 (January 1995).

50. Personal communication with a Russian enrichment expert, June 2000.

51. Anton Khlopkov "The Iranian Nuclear Program in the Russian-American Relations" (PIR Center: Moscow, 2001).

52. "Russia ID'd as an Iran Atomic Supplier," Associated Press (20 November 2003); "Minatom Denies Russian Participation in Supplying Iran with Equipment for Enriching Uranium," Interfax (20 November 2003). The articles are available at ⟨www.ransac.org/Projects and Publications/News/NuclearNews/1120200343218PM.html#2G⟩.

53. "People in the South Urals Phone the FSB," *Chelyabinskii Rabochii* (27 October 2000).

54. One proposed criteria of the weapons origin of the HEU was its age. It was argued that HEU age could be determined by measuring the daughter products, Th-230 and Pa-231, of U-234 and U-235, respectively, by first chemical separation of the daughter products and measuring them by alpha-spectrometry. (A. R. Moorthy and W. Y. Kato, "HEU Age Determination," paper presented at the 35th

Institute of Nuclear Material Management Annual Symposium, Naples, FL, July 17–20, 1994.)

55. P. Herman et al. “Sharing the Challenges of Nonproliferation,” *Science and Technology Review* (September 1997): 14–23.

56. At Portsmouth, Russian monitors verify the receipt of 30B containers with LEU UF6, container storage, sample withdrawal and analysis, and MC&A data. See Wilson Dizard III “Enrichment News,” *Nuclear Fuel* (18 November 1996): 4.

57. Andrew Bieniawski and Vladislav Balamutov, “HEU Purchase Agreement,” *Journal of Nuclear Materials Management* (February 1997): 7–8.