RUSSIA'S GASEOUS CENTRIFUGE TECHNOLOGY AND URANIUM ENRICHMENT COMPLEX

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Illustration on the cover: Centrifuge equipment at the SKhK enrichment plant in Seversk (source: *Atomium*, No. 2, 2003).

LIST OF ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AEKhK	Anagrsk Electrolysis and Chemical Plant, Angarsk
Centrotech-TsKBM	(now Centrotech-EkhZ) centrifuge R&D unit
CNEC	Committee for Nuclear Energy of China
GAZ	Gorkovski Automobile Plant
Gen	centrifuge generation
GSPI-11	Design Bureau 11 (now the Institute of Power Technologies, VNIPIET), St.Petersburg
Dyagterev Plant	a centrifuge manufacturing facility, Kovrov
EKhZ	Electrochemical Plant, Zelenogorsk
FSB	Federal Security Service
HEU	highly-enriched uranium
IAEA	International Atomic Energy Agency
I&C	instrumentation and control
IPPE	Institute of Physics and Power Engineering, Obninsk
KI IMP	Kurchatov Institute’s Institute of Molecular Physics, Moscow
KUMZ	Kamensk-Uralski Metallurgical Plant
LEU	low-enriched uranium
Minatom	Ministry of Atomic Energy
Minsredmash	Ministry of Medium Machine-Building
MT	metric ton
NFCD	Minatom’s Nuclear Fuel Cycle Department
NTS	Science and Technology Council
OKB GAZ	Special Design Burea GAZ, Nizhnii Novgorod
OKB LKZ	Design Bureau of the Leningrad Kirov Plant (now the Central Design Burea of Machine-Building, TsKBM, , St.Petersburg)

SKhK	Siberian Chemical Combine, Seversk
SverdNIIKhimMash	Sverdlovsk Institute of Chemical Machine-Building, Yekaterinburg
SWU	Separative Work Unit
Tenex (Techsnabexport)	Minatom’s uranium trading company
TRC	Transparency Review Committee
TsKBM	Central Design Burea of Machine-Building, St.Petersburg
UEKhK	Urals Electrochemical Combine, Novouralsk
USEC	United States Enrichment Corporation
VIAM	Institute of Aviation Motors
VNIIKhT	Institute of Chemical Technologies, Moscow
VNIITF	Institute of Technical Physics, Snezhinsk
VNIPIET	Institute of Power Technologies, St.Petersburg
VPO Tochmash	Production Association “Precision Machines Plant,” Vladimir

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-60s, 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 Anagrsk Electrolysis and Chemical Plant (AEKhK) in Angarsk, Irkutsk region (see Appendix A: Soviet/Russian Uranium Enrichment Sites). All four were originally established as gaseous 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.

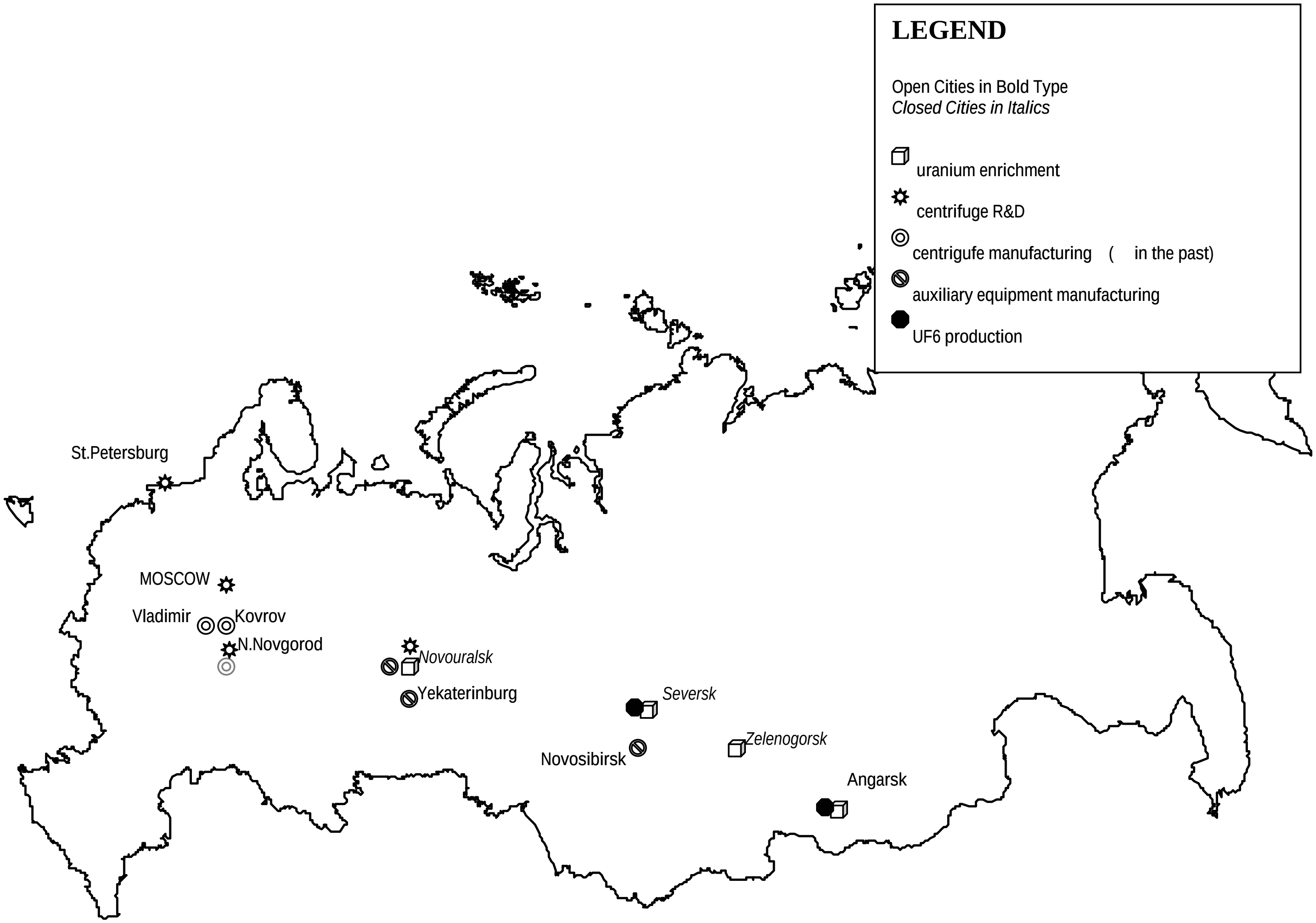
Russia's enrichment industry and technologies are also important from the international security standpoint. The enrichment plants, for example, are central to the implementation of the 1993 U.S.-Russian HEU agreement, perhaps the most important nonproliferation, arms control and nuclear transparency 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 risks and opportunities requires better understanding of the Russian enrichment complex and technologies, including their history, current state, and future directions. The report below seeks to address some of these topics. The report begins with a brief overview of the history of centrifuge development and deployment in Russia and its centrifuge R&D and production infrastructure. It then discusses the post-Soviet transition of the uranium enrichment complex, its major missions, and relevant issues of international security. The report is based on public information.

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 (SverdlNIIKhimMash, Yekaterinburg)	SverdlNIIKhimMash 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, etc.).

Map 1: Russia’s enrichment complex



KAMENEV'S CENTRIFUGE

Research on the use of centrifuge methods for isotope separation in Russia was started in the mid-1930s in the Kharkiv Institute of Physics and Technology by Fritz Lange, an escapee from Hitler's Germany. By 1944, Lange had developed a slow, thick-walled centrifuge (250 mm in diameter, 600 mm long; 18 m/s wall rotation speed), which, together with auxiliary equipment, weighed 2.5 t.[1] The project produced valuable R&D experience but no working design and was cancelled in 1951. The hope was now pinned on the group of German and Soviet scientists, lead by Prof. Max Steenbeck, which worked at the nuclear R&D center in Sukhumi on the Black Sea. To strengthen the centrifuge project, around 1952, the German group was transferred to the Design Bureau of the Leningrad Kirov Plant (OKB LKZ, now the Central Design Burea of Machine-Building, TsKBM, in St.Petersburg). The enrichment section of Laboratory 2 in Moscow (currently the Kurchatov Institute of Atomic Energy), headed at that time by Isaac Kikoin, was also heavily involved in centrifuge R&D. The development of centrifuge enrichment technology was conducted in parallel with rapid advances in the development and deployment of the gaseous diffusion technology.

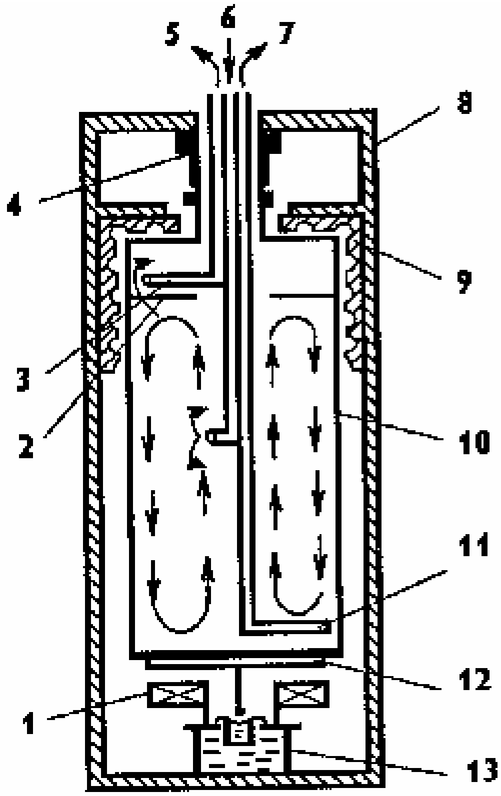


Fig. 1: Kamenev's centrifuge (source: A. Plotkina "The Development and Improvement of the Centrifuge Method to Separate Uranium Isotopes in Russia," *AtomInform* (No. 6) (1996): 50-53.).
1 – electric motor stator; 2 – baffle; 3 – top scoop (light fraction); 4 – magnetic ring bearing; 5 – enriched product; 6 – feed; 7 – tails; 8 – housing; 9 – molecular pump; 10 – centrifuge rotor; 11 – bottom scoop (heavy fraction); 12 – electric motor rotor; 13 – oil damper

The initial focus of the Steenbeck group was on a 3-meter long supercritical centrifuge spinning at a speed of 240 m/s, two pilot units of which were eventually manufactured by the TsKBM.[2] Two major hurdles, however, became apparent: a) long, supercritical

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[1] A. Plotkina "The Development and Improvement of the Centrifuge Method to Separate Uranium Isotopes in Russia," *AtomInform* (No. 6) (1996): 50-53.

[2] 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.

machines required careful balancing by hand and thus were not suitable for industrial manufacturing; and b) there was no apparent solution on how to transfer the uranium gas from one centrifuge to another to link centrifuges into a cascade.

The critical breakthrough was made in early 1952, when Evgeni Kamenev, a member of the Kikoin group in Moscow, proposed a concept of a short subcritical centrifuge, that incorporated elements of Steenbeck's long centrifuge and novel proposals by Russian scientists (see Fig. 1). In February 1953, the concept (including design parameters) was briefed to and adopted by the TsKBM and the Steenbeck group. In December 1953, Kamenev presented a model of his centrifuge. Its rotor was made of V-95 aluminum alloy; was 100 mm in diameter, 500 mm long and 1 mm thick; and was designed to spin at a speed of 320 m/s. Russian experts point out that today's centrifuge technology would not have happened without "a short stiff rotor by E.M.Kamenev, thin needle bottom bearing and [magnetic] top bearing by M.Steenbeck, and the idea of gas-dynamic transfer of [UF6 by stationary scoops] from one centrifuge to another by I.K.Kikoin," which were the basis of Kamenev's concept.[3] Another important idea was to surround the rotor with a housing that was intended both to contain debris in the case of centrifuge failure and to serve as a molecular pump stator.[4] Most of these ideas have been incorporated in all subsequent centrifuge designs in Russia and in other countries (see Table 2).

Table 2: Principal ideas behind Kamenev's centrifuge

DESIGN ELEMENT	AUTHOR	SIGNIFICANCE
short, stiff, subcritical rotor	Kamenev	- simplified manufacturing and operation - ease of mass production
molecular pump	Kamenev	- reduced friction losses - protection of other centrifuges in case of centrifuge failure - prevention of UF6 leakage
needle-point bottom bearing with an oil damper	Steenbeck	- self-balancing spinning top - low energy consumption
non-contacting top bearings of ring magnets	Steenbeck	- low energy consumption - self-balancing spinning top -reduced load on the bottom bearing
stationary scoops	Kikoin	- improved countercurrent flow - sufficient pressure differential to transfer gas to another centrifuge

A smaller (58-300 mm) machine, based on the same principles, was demonstrated in the summer of 1953 by Gernot Zippe, a capable engineer from Austria, prior to his departure

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[3] Ibid.

[4] 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.

from the project in 1954.[5] Upon his return to the West, Zippe (and his co-worker, R.Scheffel) patented the design, which subsequently has become known throughout the world as the Zippe centrifuge. Soviet scientists and engineers were bewildered and upset. According to A.Plotkina, a veteran of the centrifuge project, “the patent was given to those, who, in reality, had not authored a single element of the centrifuge.” The Soviet Union offered no reaction to the news, however. According to Nickolai Sinev, the Soviet chief centrifuge designer during the 1950s,

> “[H]aving learned about this plagiarism, the Soviet atomic management decided not to react to this information – to keep quiet in order not to give any indication that the USSR was working on a new, progressive method of uranium enrichment. Let them think that the USSR … continued using the inefficient gaseous diffusion method. Indeed, that was the price of the concealment for over 30 years of the industrial deployment of a new economic uranium enrichment technology in the USSR.”[6]

Plotkina adds bitterly that “the damage to the morale and the economic damage done by the notorious regime of secrecy, which did not allow the USSR to patent abroad the Soviet centrifuge design, was [enormous].”[7] It should be noted, however, that although Zippe was not the author of the centrifuge, he did make an important contribution to the centrifuge project by demonstrating the viability of the proposed design concepts.

CENTRIFUGE DEVELOPMENT AND DEPLOYMENT

The Kamenev centrifuge became a prototype for a line of industrially-manufactured centrifuges that allowed the Soviet Union to increase its uranium enrichment capacity and to phase out the gaseous diffusion technology (for a generalized timeline of these developments see Fig. 2).

First steps towards industrial deployment of centrifuges were made in the early 1950s. In 1953-54, the TsKBM manufactured and tested several subcritical centrifuges. This work led, on April 1, 1954, to the establishment of a centrifuge R&D laboratory at the USSR’s primary uranium enrichment facility in Novouralsk.[8] In October 1955, the Soviet government resolved to build in Novouralsk a 2,435-centrifuge pilot plant. The plant was designed by St.Petersburg’s GSPI-11 (now the Institute of Power Technologies, VNIPIET). The Leningrad Kirov Plant manufactured the centrifuges. The pilot plant was accommodated in the building of the USSR’s first gaseous diffusion plant (the D-1 plant in Module 0 of the UEKHK complex).[9] It was brought into operation on November 2-4,

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[5] Based on interviews of David Albright, a centrifuge technology expert, with Gernot Zippe. According to Zippe, his machine had a diameter of 58 mm and was 25 (not 30) cm long. (T D.Albright et al Plutonium and Highly Enriched Uranium 1996.) The machine he demonstrated in the University of Virginia upon his return from the USSR, presumably an optimized version of the Russian centrifuge, had a diameter of 74 mm and the length of 332 mm and was designed to spin at 350 m/s; see: Stanley Whitely “Review of the Gas Centrifuge until 1962. Part II: Principles of High-Speed Rotation,” *Reviews of Modern Physics*, vol. 56 (1), (January 1984): 67-97.

[6] N.M.Sinev *Enriched Uranium for Atomic Weapons and Power*, (Moscow: TsniiAtomInform, 1991).

[7] A. Plotkina “The Development and Improvement of the Centrifuge Method to Separate Uranium Isotopes in Russia,” *AtomInform* (No. 6) (1996): 50-53.

[8] V.Shidlovsky and G.Solovyev “History and Status of Industrial Isotope Separation in Russian Federation,” (undated, provide to the author by David Albright).

[9] The D-1 plant was started up in 1948 and shutdown in 1955.

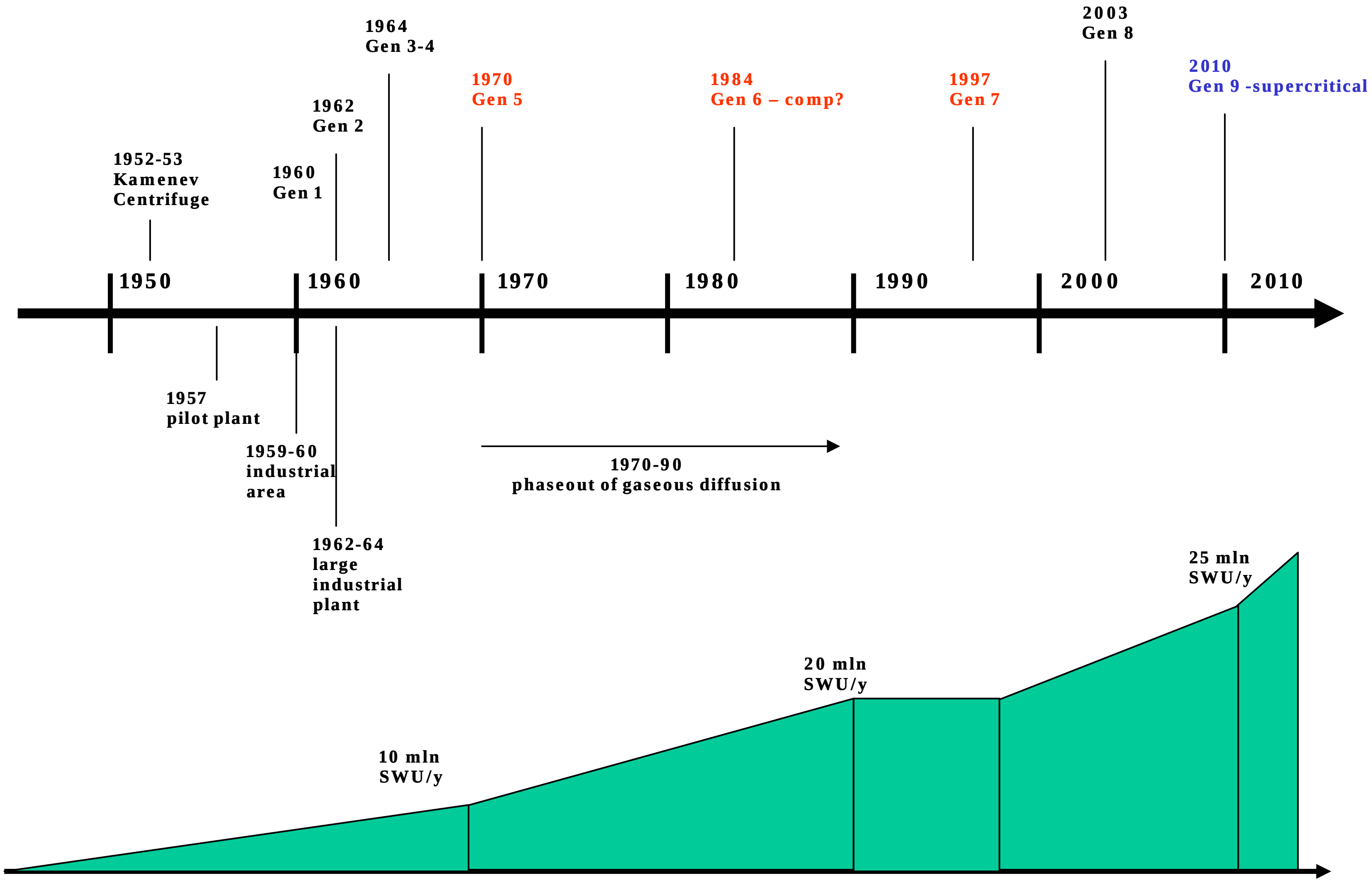

Fig. 2: Notional timeline for centrifuge development and enrichment capacity growth.

1957 and reached capacity on January 15, 1958. A major objective of the project was to assess the reliability and performance of the centrifuge and instrumentation and control (I&C) systems.

The operational experience of the pilot plant was analyzed in 1959 at Minsredmash's (the Ministry of Medium Machine-Building, Minatom's predecessor) Science and Technology Council (NTS) and became a basis for a decision to initiate mass production of centrifuges at the machine-building plants in Gorkii (now Nizhni Novgorod), Vladimir, and Kovrov (see below) for industrial deployment. The first industrial facility, equipped with first-generation (Gen 1) centrifuges, was established in an area inside one of the gaseous-diffusion buildings in Novouralsk (for a discussion of centrifuge generations see Table 3).

Table 3: Centrifuge Generations

Generation	**Years of design, production, deployment**	**Comments**
Prototype (Kamenev centrifuge)	developed 1952-55 operation (pilot plant) 1957	
1	production 1960 first deployed 1961	
2	deployment 1962 reliability R&D 1966-70 operation until 1972-74?	multi-layered arrangement used for the first time
3	deployment 1963-64 reliability R&D 1966-70 operation until 1972-74?	
4	reliability R&D 1966-70	
5	stand testing 1966-70 first deployment 1970 mass deployment 1971-75	massive failures in 1972 50 percent of the current centrifuge park According to design specification centrifuge lifetime is 12.5 yrs; reliable operation is less than 25 years
6	R&D in early-mid 1970s first deployment 1984	based on the R&D effort to resolve reliability problem of Gen 5 centrifuges; possibly utilizes composite materials According to design specification centrifuge lifetime is 15 yrs; reliable operation is projected to 30 years. electricity consumption is 60 kWh/SWU
7	beginning of R&D 1978 pilot production 1982 pilot unit testing 1991 mass production since 1997 first deployment 1997	centrifuge capacity is a factor of 2 higher relative to Gen 5 electricity consumption is 50 kWh/SWU; overall power requirements are 100 kWh/ SWU*
8	beginning of R&D 1997 possible deployment 2003	centrifuge capacity is a factor of 2 higher relative to Gen 6
9	design selection 2004 mass production 2010	supercritical rotor capacity is to increase by a factor of 2 relative to Gen 7

* Uranium enrichment plants have extensive non-centrifuge electric power requirements including heating of UF6 in cylinders; operating cold traps, pumping cooling water and process gases (air and nitrogen) and others.

On August 22, 1960, the Soviet government resolved to build in Novouralsk an industrial-scale centrifuge facility. The plant, which was designed by the VNIPIET, was installed in a brand-new building (Module 4). It was brought into operation in three phases from 1962 to 1964. The plant employed centrifuges of the second and third generations, which, for the first time, were installed in multiple layers.[10] (Subsequently, the plant was modernized two times and currently uses centrifuges of the sixth generation.) Indeed, initially, the production plants supplied centrifuges as individual units. Later on, the enrichment facilities began receiving centrifuges assembled into sections ("aggregates") containing 20 (two rows of tens) machines each, which were installed on top of each other up to seven layers high (see Fig. 3). (As individual machines fail, they are valved off and the section continues to operate at a reduced capacity; when the capacity is reduced below specified limit, the section is removed and is replaced with a new one.) This arrangement allowed Soviet specialists to install a very large number of centrifuges inside the halls of the former gaseous diffusion plants. At the same time, the multi-layered arrangement has inhibited the development of longer centrifuges (which could have resulted in higher separation capacities) because it was more economical to fit centrifuges of new models into the space allotted to them by the existing layers.[11]

Fig. 3: Centrifuge hall of the Angarsk enrichment facility (source: www.aecc.ru/prod_sepr.php).

Second-generation centrifuges were presumably made of an aluminum alloy developed by the Institute of Aviation Motors (VIAM) in cooperation with centrifuge design institutes and manufacturing plants.[12] Aluminum was selected because of its low specific weight; and the VIAM's task was to create a high-strength but light-weight alloy. The institute already had considerable experience in developing aluminum alloys for use in aircraft and missiles.[13]

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

[11] A. Senchenkov and S. Senchenkov "Gaseous Centrifuges," in V.Baranov (ed.) *Isotopes: Properties, Production, Application*, (Moscow: Izdat, 2000).

[12] Iosif Fridlyander "Secret Mission. Kruzhevo of Centrifuges," *Literaturnaya Gazeta*, (October 31, 2001).

[13] Presumably, the new material was similar to Alloy 1420 developed for aviation purposes. In addition to aluminum, Alloy 1420 contains 2% lithium, 5.5% magnesium, and 0.1% zirconium. Alloy 1420 is known to be corrosion-resistant, have high tensile strength, amenable to welding, and light weight. "Krylaty Metal 1420," *NG Nauka*, (November 17, 1999).

The production of the new material was assigned to the Kamensk-Uralski Metallurgical Plant (KUMZ). In 1963, a group of specialists from VIAM, KUMZ, and the Aviation Ministry's Metallurgical Department were awarded a prestigious Lenin prize for the project.

In 1966-1970, the UEKhK R&D unit conducted further reliability research for industrial operation of centrifuges of the second, third, and fourth generations as well as test-stand operation of Gen 5 centrifuges.[14] 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.[15] This effort was based on Gen 5 centrifuges, which were first installed in 1970 and were deployed on a massive scale in 1971-75.[16]

In 1972, after two years in operation, Gen 5 centrifuges began to fail in large numbers. An investigation by experts from VIAM, TsKBM, and enrichment facilities allowed them to correct the problem and established a basis for the development of the sixth generation of centrifuges. The R&D on the 6th generation machine was completed in the mid - to late 1970s and its initial deployment began in 1984.[17] Possibly, the sixth generation machine was the first model to use composite materials for reinforcement purposes.

The development of the 5th and 6th generation machines allowed the enrichment complex to end in the late 1980s – early 1990s the use of the gaseous diffusion technology. As a result, the electricity consumption for enrichment operations decreased by an order of magnitude while the enrichment capacity increased by a factor of 2-3.[18] By the late 1980s, the capacity reached the level of approximately 20 million SWU/y.[19]

By the late 1990s, the enrichment complex was equipped with approximately equal numbers of centrifuges of the 5th- and 6th generations. [20] 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 5th generation machine was 12.5 years; the actual lifetime is under 25 years.[21]) All Gen 5 machines will have to

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

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

[16] For example, in 1971-75, the deployment of Gen 5 centrifuges in buildings formerly containing gaseous diffusion machines began at the UEKhK in Novouralsk.

[17] Based on V.Shidlovsky "On the Prospects and Plans for Modernizing Enrichment Facilities," *Atompressa*, 36, (September 2000).

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

[19] 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).

[20] 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, V.Tolstoi "The Status and Perspectives of Separation Production," *Atomnaia Energiia*, vol. 89, No. 4, (October 1, 2000) 338-343.

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

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.[22] Gen 5 machines, including those in the HEU (up to 95 percent U-235) production cascades, are being replaced with centrifuges of the 7th generation. The retired centrifuges are dismantled and valuable materials (including maraging steel, aluminum, copper, and silver) are recovered at the Sverdlovsk Institute of Chemical Machine-Building (SverdNIIKhimMash) in Yekaterinburg.[23]

The development of the 7th-generation centrifuge began at UEKhK in 1978 and a pilot section of new machines was manufactured in 1982.[24] Pilot operation and industrial deployment of Gen 7 machines began in 1991 and 1997 respectively. In 1998, Russian experts began R&D to develop the 8th generation centrifuge (designated PGTs-8). Its deployment is tentatively scheduled to begin in 2003-04.[25] 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.[26]

The 8th 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) (the lead designer is Centro-Tech EkhZ, see below), b) a composite rotor with composite bellows) (UEKhK, Novouralsk), and c) a metal-based reinforced "rigid" rotor (OKB GAZ).[27] 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 6th 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, developed by

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

[23] Reportedly, the dismantlement of one 20-centrifuge section yields 500 kg maraging steel, 200 kg aluminum, 17 kg copper, and 20 g silver. See: Mark Hibbs and Pearl Marshall "Urals Plant Enriching Tails for both Minatom and Urenco," *Nuclear Fuel* (October 6, 1997).

[24] A.Knutarev "We Have Something to Be Proud Of," *Atompressa*, 22, (July 1999).

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

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

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

experts from the Institute of Energy Technologies in St. Petersburg (VNIPIET), Minatom, and the enrichment enterprises, 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.[28]

Centrifuge design

For every generation (at least through the early 1990s), Soviet designers developed both sub- and supercritical centrifuges.[29] Supercritical machines are currently in use to separate stable non-uranium isotopes. Subcritical centrifuges with a diameter of 12-16 cm and a length of approximately 60-70 cm, however, have become the technology of choice for uranium enrichment as it was judged that the Soviet machinery industry was best suited for volume-production of relatively simple, but high-quality and reliable items.

The first working subcritical centrifuges that were designed and tested in the early 1950s had an estimated separative capacity of 0.4 SWU/y. The development of the subsequent generations of centrifuges involved optimization of centrifuge geometry and increase in speed, which, in turn, required stronger materials to manufacture centrifuge rotors. This progress generally allowed the designers to increase the capacity of individual machines by about 30 percent per generation.[30] (Table 4 is based on research by David Albright and represents a notional trajectory for performance improvements.) Soviet designers also had to address the issues of

- long-lasting bottom-bearings;[31]
- longevity of the rotor under very high loads and corrosive media;
- cascade protection against a catastrophic destruction of a single centrifuge;
- instrumentation and control equipment for both individual centrifuges (including sensors of the velocity and load and isolation valves to isolate the centrifuge from the cascade in the event of rotor destruction) and for a production cascade as a whole; and
- uninterrupted power supply.

Unlike Urenco's all-composite centrifuges, Russia's more recent centrifuges are believed to be made of composite-reinforced metal. Again, this reflects the Soviet emphasis on centrifuges that are cheap and easy to mass-produce. In such centrifuges, high-modular aramid fiber Armos is wrapped around the metal rotor at an angle to provide for

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

[29] E.Mikerin, V.Bazhenov, G.Solovyev "Directions in the Development of Uranium Enrichment Technology," (Minatom, undated).

[30] A. Senchenkov and S. Senchenkov "Gaseous Centrifuges," in V.Baranov (ed.) *Isotopes: Properties, Production, Application*, (Moscow: Izdat, 2000).

[31] According to David Albright, "[T]he bottom bearing initially lasted about three years, although current ones last as long as the machine. This increase in the lifetime implies that the design of the bearing may have shifted from a hard metal pin rotating in a socket to a spiral-grooved design in which the pin pumps oil between itself and the socket, dramatically reducing friction and extending the bearing's lifetime." D.Albright et al *Plutonium and Highly Enriched Uranium 1996*.

tangential rigidity and to minimize lateral bending.[32] High-strength graphite composite fiber is then wrapped around on top of the first material to provide for strength.

Table 4: Estimated increase in separative capacity of Russian centrifuges*

Generation	Separative capacity, SWU/y	Comments
1	0.4	Diameter = 10 cm, speed = 340 m/s
2	0.6	Machine optimized; diameter = 12 cm; speed = 360 m/s
3	1.0	Same except speed 425 m/s
4	1.4	Same except speed 475 m/s
5	1.9	Same except speed 530 m/s
6	2.5	Same except speed 580 m/s
7	3.2	Same except speed 630 m/s
8	4.2	Same except speed 690 m/s

* Adopted from D.Albright et al *Plutonium and Highly Enriched Uranium 1996*, 106.

** Note that the numbers are not fully consistent with data in Table 3

The average annual material requirements for centrifuge production provide an insight into what newest-generation centrifuges in Russia are made of (in MT; presumably the material requirements are per about 150,000 centrifuges):[33]

aramid fiber	109	alloy 1960	1,339
graphite fiber	57.4	steel	8,273
PAN-fiber	218	polymetals	288
fiberglass	71.6	resins	347

The emphasis on the ease of manufacturing and reliability remains an important element of the Russian centrifuge design philosophy: according to Russian centrifuge experts, "[A]n economic centrifuge is a centrifuge that a particular country is capable of develop quickly and to produce in mass quantity. This, for example, explains why the Russian subcritical centrifuges, developed over 20 years ago, remain economically competitive [at present]."[34] Russian experts also believe that future missions, including stripping of the past enrichment tails would require a significant increase in the enrichment complex's capacity and that an optimal centrifuge design and the efficiency of the centrifuge manufacturing process would be particularly important.

GASEOUS CENTRIFUGE DEVELOPMENT AND PRODUCTION INFRASTRUCTURE

The development and industrial application of the centrifuge technology would not have been possible without a mature centrifuge R&D and manufacturing base.

Centrifuge R&D complex

Centrifuge R&D calls for a highly specialized expertise and capabilities. The centrifuge design process includes the use of specialized software to calculate the hydrodynamics of

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[32] A possible arrangement could include the angle of 20-30 degrees (both clock- and counter-clockwise).

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

[34] A. Senchenkov and S. Senchenkov "Gaseous Centrifuges," in V.Baranov (ed.) *Isotopes: Properties, Production, Application*, (Moscow: Izdat, 2000).

the main section of the rotor and to establish its optimal performance as a function of the amount of gas inside, feed rate, location and angle of the feed pipe, and temperature distribution. The high-fidelity calculations are used to optimize the centrifuge's separative capacity while providing for its compatibility with the existing piping, motor's capacity, rotor's temperature, etc. Computer modeling of processes in the end-areas of the centrifuge is more difficult and less precise. The development of the corresponding components therefore requires a large number of experiments. A pilot unit of an optimized centrifuge is then manufactured and tested on a test stand thirst without uranium and then with UF6. Testing of pilot sections and cascades is also conducted to determine centrifuge reliability and efficiency. In parallel, manufacturing technologies and procedures for mass-production of new machines are formulated and optimized. The R&D and production cycle could take many years to complete. Advances in other relevant science and technology fields (electronics and electrical equipment, facility engineering, advanced materials, UF6 chemistry and processing, I&C, etc.) are also critical to centrifuge development and deployment.

In Russia, centrifuge R&D is conducted at several institutions of Minatom and other agencies:

- The Central Design Bureau of Machine-Building in St.Petersburg has been the primary designer of the first six generations of centrifuges (including most currently operating machines) and related equipment (piping, valves, etc.). In 1989, its centrifuge unit, known as Centrotech-TsKBM, joined its forces with the Electro-Chemical Plant in Zelenogorsk to become the Science and Technology Center Centrotech-EKhZ. The Center is presently Minatom's lead centrifuge designer. It conducts a full R&D cycle, manufactures pilot centrifuges, and produces a variety of stable isotopes for medical and industrial purposes. In particular, the Bureau is a lead designer of a supercritical centrifuge composed of several short rigid rotors connected by steel bellows. The TsKBM also produces turbo-molecular pumps and other deep-vacuum systems used in isotope separation applications.[35]
- The Special Design Bureau OKB GAZ has traditionally played an important role in designing centrifuges. Among its present missions is designing a metal-based reinforced rigid rotor of a supercritical centrifuge. Presumably, the OKB GAZ is an element of the Design Bureau of the Machine Building (OKBM) in Nizhni Novgorod or OKBM's parent facility – the Nizhegorodski Machine-Building Plant. According to some publications, however, it is a part of the Gorkii Automobile Plant (GAZ).[36]
- R&D units and pilot facilities of the primary enrichment complexes are critical to both centrifuge development and deployment. In particular, the pilot plant and the

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[35] TsKBM was established in 1945 and, as of 1991, employed 1,500-2,000 workers. In addition to centrifuge related equipment, it develops and produces compact nuclear reactors (including the Topaz-2 space reactor), nuclear power plant equipment (including the fuel loading machine for the RBMK reactors, and naval propulsion coolant pumps), and furniture. (*Russian Defense Business Directory*, (Washington, DC: U.S. Department of Commerce, 1995).

[36] A. Plotkina "The Development and Improvement of the Centrifuge Method to Separate Uranium Isotopes in Russia," *AtomInform* (No. 6) (1996): 50-53.

design bureau of the UEKhK complex in Novouralsk were the principal designers of the seventh-generation centrifuge and are the lead designers for an all-composite supercritical machine.

- The Institute of Aviation Motors (VIAM) in Moscow develops structural materials for centrifuges. According to Minatom enrichment experts "there has been a very strong correlation between the development of isotope separation centrifuges and the development of rocket motors for the Russian space program."[37]
- Kurchatov Institute's Institute of Molecular Physics (KI IMP, Moscow), the successor of the original enrichment section in the Laboratory 2, is also a major player in the centrifuge development area. The KI IMP has its own experimental centrifuge cascade, which is used for technology development and separation of non-uranium isotopes, and a pilot mechanical plant. The institute works on both advanced centrifuge designs and chemistry aspects of isotope separation.[38]
- The Institute of Chemical Technologies (VNIIKhT, Moscow) is a center of expertise on UF6 chemistry and processing technologies.
- St.Petersburg's Institute of Energy Technologies (VNIPIET) is another critical participant in the development of the centrifuge enrichment industry in Russia. The institute has designed all of Russia's enrichment facilities. It also worked with the UEKhK plant in Novouralsk and other facilities to develop an integrated two-level I&C system (for individual centrifuges and plant-wide) currently in use in the Russian enrichment complex.

Many other facilities (for example, the Institute of Chemical Machine-Building in Yekaterinburg, SverdlNIIKhimMash, a designer of nuclear fuel cycle equipment) have also made important contributions.

Centrifuge equipment manufacturing

At present, the production of centrifuges takes place at the VPO Tochmash (Production Association "Precision Machines") in Vladimir and the Dyagterev Plant in Kovrov.[39] Both facilities are a part of the Russian military industrial complex and, in addition to centrifuges, manufacture a variety of conventional weapons systems and components as well as civilian products.[40] In the past, centrifuges were also produced by GAZ. GAZ –

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[37] E.Mikerin, V.Bazhenov, and G.Solovyev "Directions in the Development of Uranium Enrichment Technology," (Minatom, undated).

[38] The KI IMP was established on the basis of the Department of Molecular Physics (Department of Thermal Control Instruments), founded on January 15, 1944. Academician Isaac Kikoin was the head of the Department since its beginning and until 1984. In addition to centrifuge methods, the IMP works on laser isotope separation (AVLIS, MLIS), theoretical aspects of isotope separation, sensor development, and fundamental research. As of 1999, the IMP had 380 employees. See information on KI IMP website: http://www.imp.kiae.ru/_eng/main_center.htm; http://www.kiae.ru/eng/str/imph/oiimph.htm; and http://www.kiae.ru/rus/inf/new/new6.htm.

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

[40] For example, the Dyagterev Plant is a major producer of light and heavy machine-guns, rocket grenade launchers, portable surface-to-air missiles, and anti-tank guided missiles. It is also a major motorcycle-production plant. In the past, the plant was subordinated to the Ministry of Defense Industry. The plant was founded in 1916 and currently employs about 20,000 people. Tochmash was established in 1936 to produce record-player pick-up needles. Currently, Tochmash manufactures "high-precision automatic machine-

Gorkovski Automobile Plant – is one of Russia's largest car manufactures. In this case, however, GAZ is possibly a code-name for the Gorki Machine-Building Plant (currently the Nizhegorodski Machine-Building Plant in Nizhnii Novgorod), a defense facility, which is heavily involved in nuclear technologies.

The centrifuge manufacturing plants are equipped with precision equipment to manufacture metallic rotors, computer-controlled filament-winding machines, polymer setting ovens, assembly conveyor belts for centrifuge rotors and machines, and centrifuge testing stands. Together, the two plants currently produce on the order of 150,000 centrifuges per year (after a slump of some 30,000 machines per years in the late 1990s).[41] They are capable of meeting 90 percent of the peak requirements under the modernization program for 2004-2006.[42] As of 2000, the principal bottleneck was the insufficient supply of aramid ("Armos") and graphite composite fiber, which, in turn, was caused by the shortage of respective feed materials (PAN-fiber for graphite-composite and Polimer M-2 material for Armos).[43] The enrichment complex has been working with the producers of these materials to eliminate shortages.

The Urals Electrochemical Combine in Novouralsk is the primary producer of automatic and I&C equipment (sensors, valves, pumps, etc.) for all four Russian uranium enrichment facilities. The electrical equipment for the centrifuge plants is provided by numerous suppliers. For example, some electrical and electronic equipment, including uninterrupted power supply systems, is manufactured by power electronics production plants in Novosibirsk.[44]

RUSSIAN ENRICHMENT COMPLEX: THE POST-SOVIET TRANSITION

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 and the Ministry of Medium Machine-Building (Minsredmash, Minatom's predecessor) 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.

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tools, automatic candy packaging machines, X-ray scanner introscopes for luggage check at the airport, automated inspection equipment, energy-saving equipment, mantle and wall clocks, electronic and other car accessories, radio sets, press dies. Tochmash is one of the biggest Russian producers of indicating and recording instruments and components for trucks and cars, tractors, trailers and other automated equipment." (Excerpted from Russia's Vladimir Oblast Regional Overview, www.bisnis.doc.gov/bisnis/country/9806vlad.htm).

[41] "Atomic Russia: Conversation with Minister Evgeni Adamov," *Zavtra*, No. 049 (12-08-2000).

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

[43] Armos aramid fiber, which is also used in body armor, is produced by the KhimVolokno company in Tver', and Kamenskvolokno in Kamensk-Shakhtinskii of Rostov region.

[44] Rolen Notman "Power Electronics Gains Strenght," *Sovetskaya Sibir'*, (15 November 2002).

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.[45] The production of auxiliary equipment at the Novouralsk complex decreased to 15-25 percent of its previous (late 1980s) levels.[46] 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. These included, as discussed in greater detail below, the 1993 U.S.-Russian HEU purchase agreement; an expansion of exports of enrichment services and enriched uranium product to West European, Far Eastern, and other countries; and contracts with Urenco and Cogema to enrich depleted uranium tailings. In addition, Russia signed a contract to construct enrichment plants in China. The Electrochemical Combine in Zelenogorsk and other facilities have also succeeded in developing non-enrichment and non-nuclear technologies and production.

The changing economic and political environment in Russia has affected the system of relations between the enrichment facilities, the supporting sector, and Minatom. The enrichment facilities continue to report to Minatom's Nuclear Fuel Cycle Department (NFCD, formerly the 4th Main Directorate). In the 1990s, however, they gained considerable independence while Minatom's influence declined somewhat and its dependence on enrichment revenues increased. At the same time, the Russian law states that only the Russian state can engage in uranium enrichment and enrichment export activities, which gives Minatom and its trading arm Tenex a central role in export operations. This complex institutional politics is further complicated by dramatic differences between the economic plight of some depressed fuel cycle facilities of Minatom's NFCD, such as the Mayak plutonium complex in Ozersk, and the relative prosperity of the enrichment facilities. To defend their interests and coordinate policies, the enrichment facilities have formed the Association of Enrichment Plants. There is, however, a considerable differentiation within the enrichment complex itself: the

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[45] For example, according to Mikerin et al "Directions in the Development of Uranium Enrichment Technology," at least 10 million SWU/y were available for exports in the early 1990s.

[46] UEKhK's presentation at the workshop on downsizing of the Minatom nuclear weapons complex; Obninsk, 27-29 June 2000.

Angarsk and Seversk facilities in particular view themselves to be poor relations of the more successful and much larger facilities in Novouralsk and Zelenogorsk. Large amounts of export money involved make the stakes high and the level of tension and resentment within and around the enrichment complex is significant.

Minatom officials, for example, have complained extensively about the increasing difficulty of controlling the enrichment facilities. According to former Minister Adamov,

> “[In the 1990s,] exporting [enrichment] facilities became independent economically and in full control of their export revenues. … Their profits represented the advantage of western prices over low cost of production in Russia, including tiny salaries of workers, low prices for electricity and heating, extremely low internal prices for feed materials, low taxes, and essentially free natural resources (water, land). Naturally, [they] paid the supporting sector according to the principle: ‘handsomely to yourself and fairly to others.’ … By treating subcontractor facilities unfairly, the exporters were undermining the basis of their own well-being. Leading scientific institutes, research and design organizations, and technology facilities were welting. Amazingly, but it is a fact that despite the profits, managers of these facilities were investing in their own production base at a level that was three times less than needed. Here you have a chicken farm where chicken do not reproduce but live by selling golden eggs produced by the previous generation of the chicken tribe. … And, at that point, we discovered that the past function of the Ministry [of Atomic Energy], that is the technological and operational management, by law, did not work. … Of course, one can ask a director-exporter to give away something in the interest of the industry. But he knows too well that there is no such law, and he will not sacrifice facility’s or his own interests in a significant way.”[47]

To deal with this situation, Minatom has developed a concept of Atomprom, which called for consolidation of finances and management of nuclear enterprises. It also has taken steps to strengthen its abilities to manage the nuclear fuel cycle facilities. The enrichment facilities, however, saw these steps as an attempt to take away their revenues. According to Nickolai Kuz’menko, the head of the city administration of Seversk

> “[In 2001] the system of arrangements between Minatom, foreign companies, and the Siberian Chemical Combine changed. The new system had been worked on by former Minister Evgeni Adamov. He had an idea of establishing Atomprom to consolidate Minatom’s budget. Atomprom was not established, but the arrangements did change. And consolidation took place. In the past, Minatom’s Techsnabexport was bringing together the Combine and foreign companies. The Combine and foreign companies negotiated contracts for enrichment services. Techsnabexport had its 1.5-2 percent commission from every contract. The profitability of these contracts was 300-800 percent. … And all these profits stayed with the Combine. It used the profits to pay taxes to the local and federal budgets and the remainder of the profits was at its disposal. Now, Techsnabexport has taken over the function of a contracting organization for enrichment services. It signs contracts with foreign companies directly. It then hires the Combine as a subcontractor and reimburses it the calculated production cost plus 18 percent profit. As a result, the profits stay with Techsnabexport and the Combine gets a small fraction [of revenues].”[48]

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[47] “Nuclear Fission,” *Vek* (September 6, 2002)

[48] Irina Zhilavskaya “Nickolai Kuz’min: They Cannot Treat Us That Way,” *Tomskii vestnik* (July 20, 2001)

By April 2002, under intense pressure from the enrichment facilities and local administrations of the associated closed cities, Minatom had modified the new arrangement somewhat to reach a compromise with the enrichment industry.[49]

Some enrichment facilities also complained that Minatom was allocating export enrichment quotas in a non-transparent and subjective way (instead of allocating them in accordance with the facilities' respective capacity shares). It was even speculated that work orders on some occasions were placed in such a way as to punish certain facility directors.[50] It is likely that while Minatom does allocate production orders in all major categories (HEU-LEU work, LEU production for Russian-designed reactors, and export orders), much depends on the ability of directors of individual enterprises to use their informal networks and to influence the process in order to maximize benefits for their respective facilities.

There are different views, however. For example, according to V.Shidlovski, former Head of Minatom's NFCD and currently (2003) Director General of the SKhK complex in Seversk (Minatom's Russian-English translation is preserved),[51]

> "There are four uranium separation plants. In the past they had reached an agreement – a corporate arrangements, essentially – to distribute export contracts proportionally the installed capacities of the separation plants. In this case the features of an enterprise are not considered. There are "mono-plants" like UECC ([UEKhK], Urals Electrochemical Combine) where the whole processes are either isotope separation or related facilities. This Combine incorporates 50% of all Russia's separation capacities. The same is true for ECP ([EKhZ], Electrochemical Plant). But the enterprises like SCC [SKhK] and Angarsk combine, even via uranium-related productions, also have sublimate lines for fluoridation of uranium. Moreover, these lines are a priori unprofitable since they were designed for other capacities, which are not in demand now. …. These aspects were not taken account of in the corporate arrangements. In addition, the program for separation capacities' development is also based on the historically formed geographic distribution, i.e. the increment is proportional. However, in the past the strategy was built against quite different criteria. These aspects have always been of my concern. I believe that it is necessary to optimize this geographic distribution of capacities considering, for example, the sublimate productions existing as at our Combine as at Angarsk combine.
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> It was not quotas that mattered. By the way, Minatom has partially modified this approach. Today all enterprises submit to Minatom their development plans and production-related programs where they indicate the revenues necessary for further development and implementation of all projects including the development of separation facilities. The second point affecting seriously the today's situation is that Tekhsnabexport doesn't act just as an agent under a contract of agency. It does a rather extensive work under contracts of work and gets benefits comparable with that of our Combine and Angarsk combine. This is one more important point. In principle, this is normal and right trend: consolidate excess profits and then don't use it in the interests of only one enterprise, which separately can be excessively profitable due to subjective reasons. Then the question arises: what happens with these excess profits, where they are channeled to, etc.? Presently, the scheme is in place where Minatom

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[49] Tatiana Vinarskaya "Seversk's 'isms': From Cataclism to Optimism," *Tomskii Vestnik* (April 17, 2002).

[50] Victor Svinin "Minatom is Skilled at Revenge," *Nezavisimaia Gazeta* (March 26, 2002).

[51] "SCC recovery (exclusive interview with SCC Director General V. Shidlovski)"; Nuclear.Ru (20 September 2003); available at http://www.nuclear.ru/eng/comments/full.html?id=20).

> distributes excess profits proceeding from the interests of the whole agency. I think this is the correct approach. As of optimization of the decision-making mechanisms and catering all interests at maximum, there is always room for perfection.”

Growth pains notwithstanding, the Russian enrichment industry has not only survived in the post-Soviet era but it has 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 requirements in former Soviet and East European countries. 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.[52]

PRODUCTION OF ENRICHED URANIUM AND ENRICHMENT SERVICES

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, re-enrichment 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 Fig. 4.[53]

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.[54] According to nuclear industry analysis, the annual enrichment requirements of the former Soviet and East European reactors power reactors could be estimated at approximately 5.3 million SWU/y.[55] 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.

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[52] 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).

[53] For Minatom capacity breakdown data, see, for example, from V.Shidlovsky “On the Prospects and Plans for Modernizing Enrichment Facilities,” *Atompressa*, 36, (September 2000).

[54] 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.

[55] Dr. Arthur Max, Nukem, personal communication, 2003.

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.[56] 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.

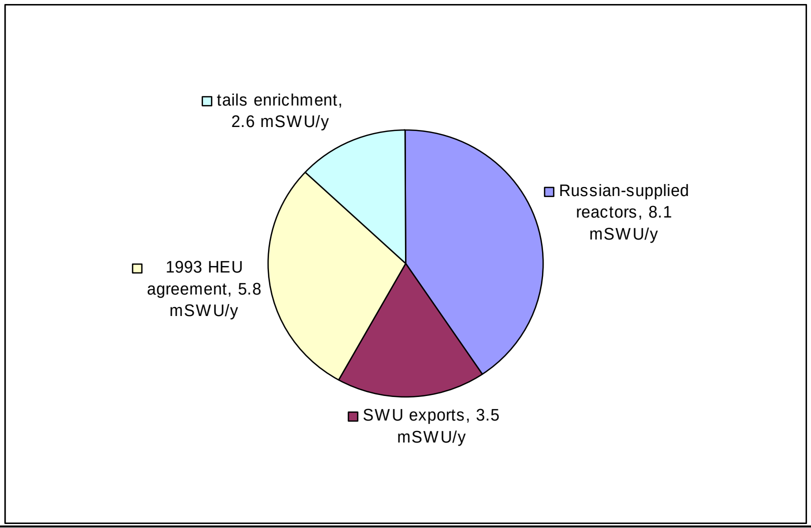

Fig. 4: Minatom's enrichment capacity utilization in 2000 assuming the total capacity of 20 million SWU/y (based on: V.Shidlovsky "On the Prospects and Plans for Modernizing Enrichment Facilities," *Atompressa*, 36, (September 2000)).

The Soviet Union entered the market in 1971 by signing a contract with France's Cogema. 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 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.)

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

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.[57]

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 heavily rely on nuclear power for energy production. The security of supply involves assurances that fresh fuel is 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).[58] 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

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[57] 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.

[58] 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.

establish such a strategic stockpile. However, the U.S. Congress refused to provide implementation funds in the FY 2004 budget.[59]

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 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."[60]

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 strictly controlled by international standards.[61] Unwanted reactor-born isotopes uranium-232 and uranium-236, as well as high-concentrations of uranium-234 presented another problem.[62]

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

[60] "Russian-U.S. HEU Agreement," *Nuclear Fuel*, (1 March 1993): 3-5.

[61] 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).

[62] 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

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 re-enriching U-234-depleted uranium tails (see Appendix B: HEU Downblending Technology and Transparency Measures).[63] (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.[64]

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.[65]

At present the HEU-downblending related activities take place at each of the four enrichment sites as well as the Mayak complex in Ozersk. 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 (Map 2). Fluorination of HEU oxide powder is carried out in Zelenogorsk (presumably from Ozersk material) and Seversk. HEU

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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*.

[63] 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.

[64] 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.

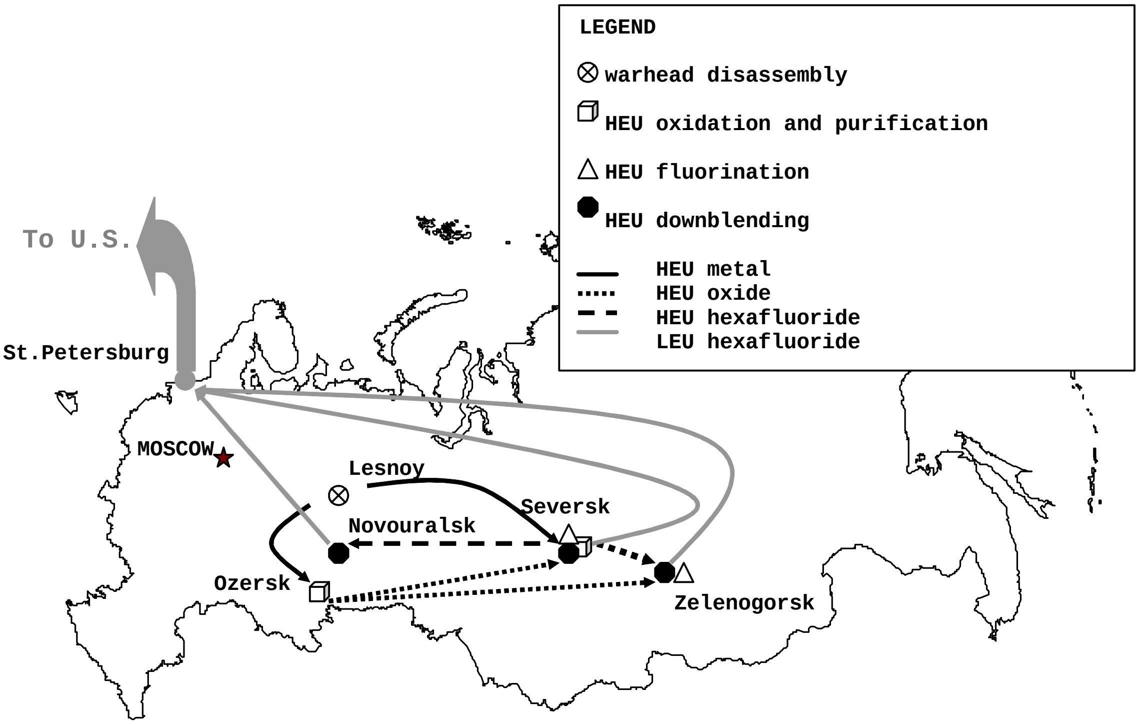
[65] "Peaceful Atom in Private Hands Could Result in Economic Wars Abroad and a Full Collapse of the Industry at Home," *Rossiyskaya Gazeta*, (5 June 1998), p 4.

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 → 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 → 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.) 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.



Map 2: HEU to LEU flows within Russia

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.[66] 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 B).

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.[67]) 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.

Re-enrichment of depleted uranium tails

Minatom's ability to re-enrich tailings is based on the low cost of production and large excess enrichment capacities. Tails re-enrichment 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 re-enrichment is also critical to the HEU downblending activities under the 1993 HEU agreement.

Re-enrichment 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 re-enrichment 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.[68] 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 re-enriching its 0.36-percent tailings.) Tailings were to be

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[66] 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.

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

[68] "Integrated Nuclear Power Development Program for 1993-2000 and to 2010," (Minatom, 1992).

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 de-emphasized. Instead, in the mid- and late 1990s, the enrichment facilities began re-enriching tails to produce the 1.5 percent blendstock for the HEU deal. Also in the late 1990s, Minatom signed tails-re-enrichment contracts with Urenco and Cogema. Under these contracts, the two companies export to Russia 5-7,000 t depleted uranium tailings (containing 0.3-0.35 percent U-235) per year.[69] 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). 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 re-enrichment of tailings accounts for approximately 35 percent, corresponding to 7 million SWU/y, of the overall SWU production in Russia.[70]) Such massive use of tailings has dramatically reduced the workload of the UF6 production plants (to 10-15 percent of their capacity).[71]

The secondary tailings, resulting from the re-enrichment of imported tailings, are the responsibility of Minatom. (Indeed, the primary motivation for Urenco and Cogema to enter into the re-enrichment 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.[72]

Re-enrichment 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.

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[69] Dr. Arthur Max, Nukem, personal communication, 2003.

[70] Dr. Arthur Max, Nukem, personal communication, 2003.

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

[72] The principal participants to 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).

Enrichment revenues

The enrichment business generates for Minatom several hundred million dollars annually ($728 million in revenues as of 2001).[73] 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 5).[74] Exports of enrichment services 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 re-enrichment 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.[75] 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.

Table 5: Minatom's estimated enrichment revenues

ACTIVITY	SALES,* MSWU/y	PRICE $/SWU	GROSS REVENUE $M	PRODU-CTION, MSWU/y	PRODU-CTION COST,** $M	NET INCOME $M
HEU-LEU	5.5	90	495 x 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 estimate.

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

[74] 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.

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

*** SWU spot market price in the fall 2003.

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."[76] 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 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.[77]

The Russian-built centrifuge plants in China, a recognized nuclear weapon states, 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.[78]

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.[79]

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

[77] Platts Nov. 12, 2001; *Nuclear Fuel*, May 17, 1999. (www.antenna.nl/wise/uranium/eproj.html#LANZHOUCENT).

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

[79] "Information," *Yaderny Kontrol*, 1, (January 1995).

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 by-pass 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, S.Chen "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges," IAEA-SM-367/8/02 (IAEA, 2001).

The Chinese plants utilize older (possibly fifth-generation) centrifuge technology and are intended to serve China's domestic customers only.[80] 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-year old."[81] 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."[82]

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

[81] Quoted in "Information," *Yaderny Kontrol*, 1, (January 1995).

[82] Personal communication with a Russian enrichment expert, June 2000.

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.[83] 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 re-configuration 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.[84]) 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, 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.[85]

IN CONCLUSION

Over a period of fifty 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

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

[84] "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/Nuclear News/1120200343218PM.html#2G

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

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 a 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 on 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 A: SOVIET/RUSSIAN URANIUM ENRICHMENT SITES (see Fig A1-4)

Urals Electro-Chemical Combine (Novouralsk)

The Urals Electro-Chemical Combine (UEKhK) and the associated closed city of Novouralsk (formerly Sverdlovsk-44) were established in 1945 to produce highly-enriched uranium for nuclear weapons. The Novouralsk location was selected because of the existence of a railway and power lines, the availability of lakes with cooling water, and the existence of a large, almost finished U-shaped building (Module 0, see Fig A1), which was originally designed as an aviation plant. The construction of the D-1 gaseous diffusion plant commenced in 1946 and its first phase was commissioned in 1948. By 1953, three more gaseous diffusion plants (D-3, D-4, and D-5 in Modules 1, 2, and 3 respectively) were constructed and brought into operation. Modules 1 and 2 featured U-shaped buildings; Module 3 consisted of four inter-connected long cascade halls and a number of additional buildings.

The Combine played a critical role in the development and industrial deployment of the centrifuge technology. The pilot centrifuge plant was installed in 1957 in Module 0 (the D-1 plant was shut down in 1955). The first industrial plant was built in three phases in 1962-64 in the 1,100-m long Module 4. The replacement of gaseous diffusion equipment with centrifuges in other buildings began in 1971 and the use of gaseous diffusion technology was fully terminated in 1987. Enrichment operations currently take place in Modules 1, 2, 3, 4; Module 0 is no longer used for enrichment. Energy to the production facility and the city is supplied from the grid, which is served by the Beloyarsk nuclear power plant (Yekaterinburg) and other plants. The city also has a back-up gas-operated power plant.

The UEKhK is the largest uranium enrichment facility in Russia, accounting for about half of Russia’s capacity. The combine comprises an enrichment sector (consisting of four modules and R&D units), an equipment production sector, support units (including repairs, power, and transportation), and a social infrastructure. The equipment-production sector manufactures automatic and instrumentation and control equipment for all of Russia's isotope enrichment facilities. The UEKhK’s total workforce is approximately 17,000 workers; the enrichment sector employs approximately 4,000 workers. Approximately 96,000 live in Novouralsk.

Electrochemical Plant (Zelenogorsk)

The Electrochemical Plant (EKhZ) and the closed city of Zelenogorsk (formerly Krasnoyarsk-45) were established in 1956 on the River Kan, approximately 70 km east of Krasnoyarsk to produce enriched uranium for the Soviet nuclear weapons program. Of 10,000 workers employed at the EKhZ approximately 3,000 are involved in isotope separation work. Zelenogorsk has a population of 67,000.

The gaseous diffusion plant at Zelenogorsk started to produce enriched uranium in October 1962 and the HEU production continued until 1989. The plant produced 40 percent of all the enriched uranium in the Soviet Union. Currently, the Electrochemical Plant accounts for 29 percent of Russia's enrichment capacity.

The enrichment complex consists of four interconnected buildings that are approximately 1-km long. Cooling water for the enrichment cascades is pumped from (and is subsequently discharged into) the River Kan. Plant's electricity requirements are covered by the nearby fossil fuel and hydro-electric plant (GRES-2).

At present, only three of the four process buildings contain enrichment equipment. The fourth building in the past contained the HEU gaseous diffusion cascade. After the end of HEU production, the cascade was shut down and tens of thousands of tons of equipment were dismantled and removed. A magnetic tape manufacturing plant, which was bought by Minatom from BASF, was installed in the empty building in the early 1990s.

Siberian Chemical Combine (Seversk)

The closed city of Seversk (formerly Tomsk-7), was established in 1949 as a home to the Siberian Chemical Combine (SKhK), Russia's largest plutonium production and fissile material management complex. Its primary facilities include a uranium hexafluoride (UF6) conversion plant (one of two such facilities in Russia), an enrichment plant, five plutonium production reactors, a chemical and metallurgical plant, a reprocessing plant, and waste management facilities. The primary production activities are supported by numerous auxiliary facilities, including research and analytical laboratories, a design bureau, mechanical and instrumentation shops, and fossil fuel power plant.

The SKhK enrichment plant was built and brought into operation in 1953 and was USSR's second (after Novouralsk) enrichment facility. It was the first operational facility in Seversk. The production of 90-percent HEU for the weapons program began in 1956 (in 1953-56 the facility produced medium-enriched uranium). In 1967, the plant started producing enriched uranium for plutonium-production and VVER reactors. The year of 1973 marked the beginning of transition to centrifuge technology. Currently the plant accounts for 14 percent of Russia's total enrichment capacity. The UF6 plant accounts for 33 percent of Russia's UF6 production capacity.

The enrichment complex consists of several long interconnected enrichment cascade halls. Cooling water is supplied from the Tom' River via a system of canals.

Seversk has a population of 119,000 of which approximately 15,000 work at the nuclear complex. The enrichment and UF6 plants employ approximately 1,400 and 1,000 workers respectively.

Angarsk Electrolyzing and Chemical Combine (Angarsk)

The Angarsk Electrolyzing and Chemical Combine (AEKhK) is located in the open city of Angarsk, approximately 30 km north-west of Irkutsk. It employs 6,400 workers and consists of the enrichment plant, UF6 conversion plant, and various support and auxiliary shops and services.

The construction of the gaseous diffusion uranium enrichment plant in Angarsk began on March 10, 1954 and the first batch of enriched uranium was produced in October 1957. The plant attained its design capacity in 1964 and, at the time, was believed to be the most efficient of the existing Soviet enrichment facilities. The enrichment plant in Angarsk has possibly never produced HEU. Instead, its partially enriched uranium product was sent to other Soviet enrichment facilities for additional enrichment.

At present, the Agrarsk enrichment facility accounts for approximately eight percent of Russia's enrichment capacity. Adjacent to the enrichment complex is a large UF6 conversion plant. It was constructed simultaneously with the enrichment facility and the production of UF6 commenced in October 1960. The UF6 plant accounts for 67 percent of Russia's UF6 production capacity.

The complex consists of two production areas that are located within a common security perimeter. Each area is served by a rail spur. The enrichment plant includes four 1 km long interconnected buildings. The conversion facility is adjacent to the enrichment plant. Cooling water for the enrichment complex is diverted from and discharged to the river through a system of canals. Heat and electricity are supplied by a fossil fuel plant. (The nearby Bratsk hydro-electric plant, one of the largest such facilities in the world, is probably another supplier of power to the nuclear complex.)

Design and layout of Soviet-built enrichment plants

There were four enrichment complexes (eight plants) built in the Soviet Union. Early plants featured U-shaped buildings (Modules 0, 1, and 2 in Novouralsk). Gaseous diffusion plants constructed in the early 1950s to early 1960s consisted of several long (sometimes over 1 km long) interconnected buildings for enrichment cascades with support equipment located in side corridors and premises. The latest enrichment plant built in Novouralsk in 1962-64 to house centrifuges is a single 1-km long building. Enrichment buildings are connected by a network of pipes, which are used to move UF6 gas between enrichment stages and to supply dry air and cooling water. Most buildings are serviced by rail.

All enrichment facilities are connected to the grid by high-voltage power lines and have large electric switchyards (substations). At each site, there is also a nearby fossil fuel power plant to supply the enrichment complex with heat and electricity.

All Soviet facilities were built near rivers or lakes, which serve as a source of cooling water. Typically, water is supplied to a water intake facility (and heat is subsequently rejected) through a system of specially built canals.

Some Soviet enrichment sites have waste management and disposal facilities including liquid waste discharge areas, holding ponds, and solid waste burial trenches. All plants have large open yards to store steel cylinders filled with depleted uranium tailings.[86]

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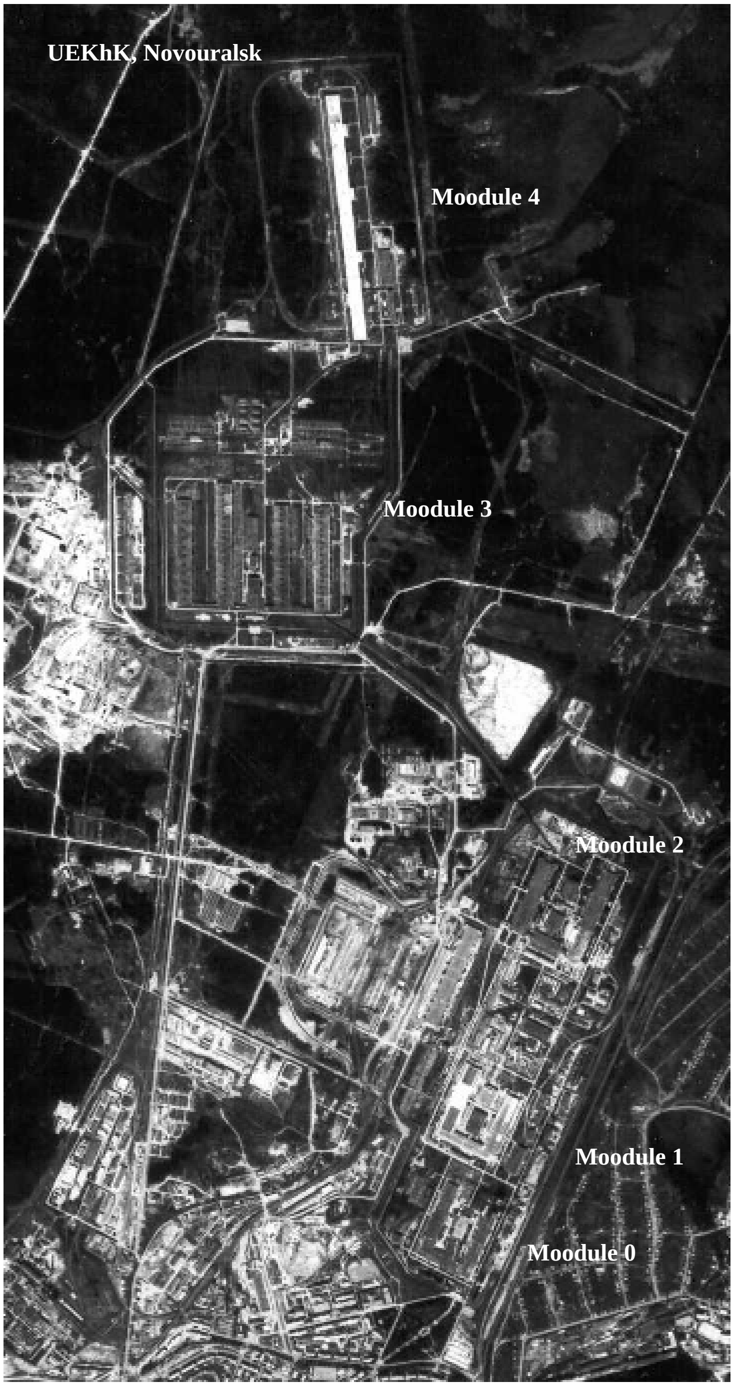
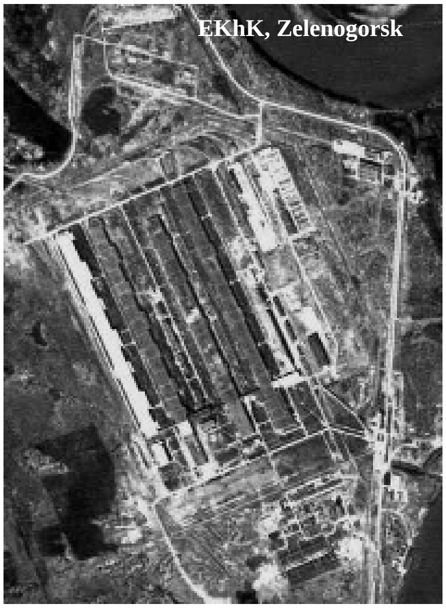
[86] For a more detailed Corona imagery analysis of individual sites see: O. Bukharin, T. Cochran, R. S. Norris "New Perspectives on Russia's Ten Secret Cities," (NRDC: Washington, DC, October 1999) and NRDC's web site "Russia's Nuclear Geography."





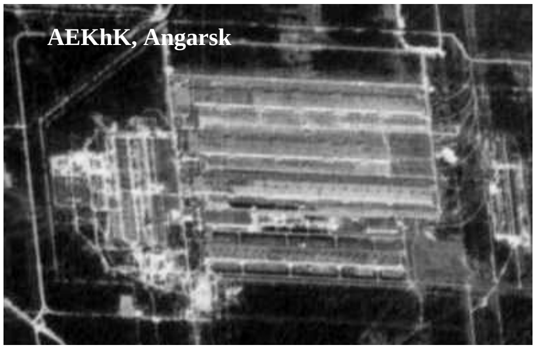


Fig. A1: UEKhK (Novouralsk) enrichment complex (source: Declassified U.S. Corona satellite imagery; Corona Mission 1111-1 23 Jul 1970).

Fig. A2: EKhZ (Zelenogorsk) enrichment complex (source: Declassified U.S. Corona satellite imagery; Corona Mission 1110-1 26 May 1970).

Fig. A3: SKhK (Seversk) enrichment complex (source: Declassified U.S. Corona satellite imagery; Corona Mission 1115-1 15 Sep 1971).

Fig. A4: AEKhK (Angarsk) enrichment complex (source: Declassified U.S. Corona satellite imagery; Corona Mission 1111-1 24 Jul 1970).

APPENDIX B: HEU DOWNBLENDING TECHNOLOGY AND TRANSPARENCY MEASURES

HEU-to-LEU downblending technology

The downblending operations under the 1993 HEU agreement utilize the UF6 process.[1] 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.[87]) In Russia, the main practical interest

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[87] 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.

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 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

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(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.)

oxides."[88] The monitors also apply tags to HEU oxide containers prior to their shipment to a downblending facility.[89]

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."[90] Both special and permanent monitors have an 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 non-intrusive non-destructive 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.

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[88] P.Herman et al. "Sharing the Challenges of Nonproliferation," *Science and Technology Review*, (September 1997).

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

[90] Andrew Bieniawski and Vladislav Balamutov "HEU Purchase Agreement," *Journal of Nuclear Materials Management*, (February 1997): 7-8.