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RUSSIAN URANIUM ENRICHMENT INDUSTRY
STATE & PROSPECTS OF DEVELOPMENT

IBR EU Power Technologies, LLC
Department of Nuclear Power Engineering & Nuclear Fuel Cycle

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2022

Russian Uranium Enrichment Industry
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EXECUTIVE SUMMARY

❖ On June 8, 2006 the RF President Vladimir Putin approved the "Program of the RF Nuclear Industry Development" aimed at further development of the Russian nuclear complex. The reforms in the Russian nuclear complex based on a new legislation were defined as one of the Program top-priority objectives.

Largely, the new "nuclear" legal base was provided within 2006-2008. The issues of principal importance in the new legal base are:

- ✓ Potentiality granted to the Russian civil nuclear complex enterprises to function as joint stock companies;
- ✓ Opportunity granted to the joint stock companies to own and manage "power" grade nuclear materials and nuclear facilities.

By the end of 2009, privatization (incorporation to joint-stock companies) of the federal state unitary enterprises within civil sector of the Russian nuclear complex planned for privatization was largely completed.

The period of 2006-2011 in corporate development of the Russian nuclear complex nuclear fuel division (uranium mining, conversion, enrichment, nuclear fuel and FA fabrication) is characterized by a string of ill-conceived administrational decisions bringing about several attempts of reforms in the nuclear fuel division corporate structure. A next in turn stage of the Russian nuclear complex nuclear fuel division reforming commenced late in 2009 after decision-making about concentrating the assets in uranium conversion and enrichment, as well as nuclear fuel and FA fabrication, within a single corporate structure set up based on FC TVEL. By early 2011, actual buildup of the FC TVEL corporate structure was completed.

Reforms in the Russian nuclear complex nuclear fuel division concerned research and production enterprises, besides the division corporate structure, included:

- ✓ Reforms of research and production enterprises internal organizational structures;
- ✓ Reforms of research and production enterprises internal business relations,

for improving the economic efficiency of the fuel division functioning as such.

Active measures aimed at reduction of management and production costs (inclusive of non-core processes divestiture, transfer of some services and subdivisions to outsourcing, introduction of programs of "SC Rosatom thrifty processes") were taken. The main costs saving measures (mainly connected with enterprises' restructuring) were implemented in the period of 2010-2012. Enterprises' restructuring associated with the withdrawal of non-core assets was largely completed to 2012. The measures directed to the costs saving are developing and implementing every year and give a positive effect.

However, approximately by 2015, SC Rosatom / FC TVEL included in their Strategies the tasks of developing the second business core (non-nuclear business). Through the development of the non-nuclear business, it was supposed to achieve the financial stability of the SC Rosatom / FC TVEL in the face of challenges and changing market conditions in the markets of the initial stage of the nuclear fuel cycle, and to create additional jobs. In 2018, a number of industry integrators for new businesses were created on the basis of TVEL Fuel Company.

❖ The last version of the State Corporation Rosatom Strategy for the period up to 2030 was updated in 2020 and approved by the Supervisory Board of the State Corporation Rosatom on April 28, 2020.

Based on the Strategy of the State Corporation Rosatom updated in 2020 for the period up to 2030, the following strategies of the development have been updated:

- ✓ Strategy of the Fuel Division of SC Rosatom - FC TVEL Strategy;
- ✓ Strategy of the Sales and Trading Division of Rosatom State Corporation - TENEX Strategy.

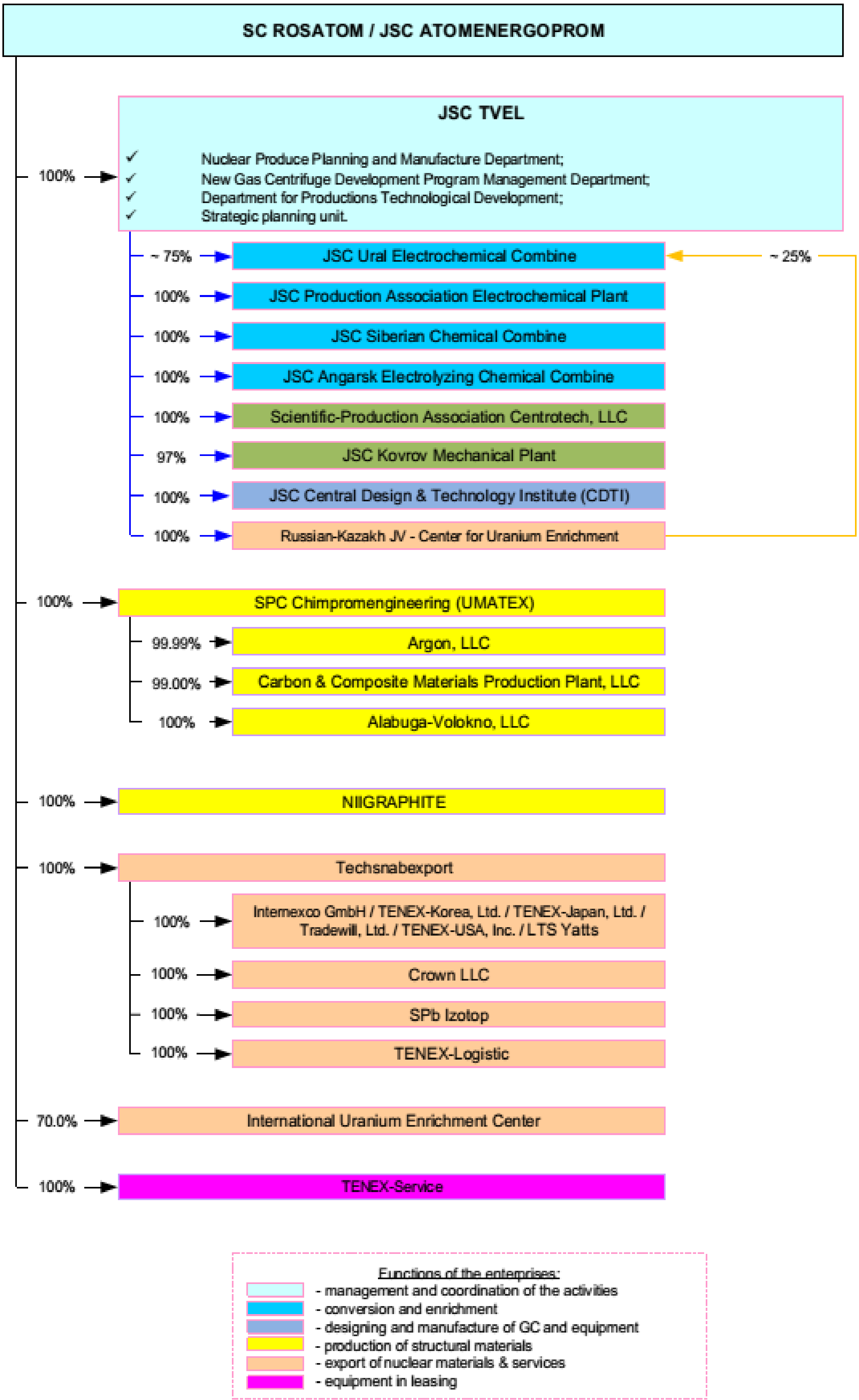

Figure 2.1
Simplified corporate structure of the Russian uranium enrichment industry

(about till 2021). IBR™ considers that at present time Russian enrichment industry tails are at the level of 0.110% ^{235}U and program of enrichment capacity development is designing based on the tails assay value ~ 0.110-0.120% ^{235}U.

Table 3.1

Optimum tails assay for FC TVEL in dependence of feed price

Actual transfer price of SWU (2021) for Russian enrichment enterprises, \$/SWU[12]	World average feed price (UF_6, 0.711% ^{235}U) \$/kgU	Optimum tails assay for FC TVEL, % ^{235}U
20	60	0.124
20	70	0.112
20	80	0.103
20	90	0.095
20	100	0.088
20	110	0.082
20	120	0.077

The meaning of Table 3.1 is to demonstrate of the cost effectiveness for FC TVEL of switching to lower-grade tails assay (% ^{235}U) with the price of feed (UF_6, 0.711% ^{235}U) expected to grow throughout the analyzed period.

Table 3.2

Payback periods for investments in increasing of Russian enrichment capacities for depleted uranium re-enrichment[13]

Feed assay, % ^{235}U	Tails assay, % ^{235}U	Price of feed purchased by FC TVEL from uranium enrichment enterprise (UF_6, 0.711% ^{235}U) \$/kgU	Payback period for investments in Russian SWU capacities modernization on the base of technology 9+, years
0.175	0.120	70	8.5
0.175	0.100	70	10.5
0.175	0.080	70	13.0
0.175	0.120	90	6.5
0.175	0.100	90	7.0
0.175	0.080	90	9.0
0.175	0.120	110	4.5
0.175	0.100	110	5.0
0.175	0.080	110	7.0

The meaning of Table 3.2 is to demonstrate the cost-effectiveness of uranium enrichment enterprises to invest in the development of a depleted uranium enrichment capacity based on the 9+ technology. An investment analysis has been performed for the option with the feed cost (depleted uranium) being equal to zero. This Table shall be understood as follows: with investments in developing the capacity of Russian uranium enrichment industry intended for enrichment of depleted uranium (0.175% ^{235}U) with tails of 0.120% ^{235}U, provided FC TVEL buys finished product (UF_6, 0.711% ^{235}U) at \$70 per kgU, the investment payback period will be 8.5 years.

[12] In fact, Russian uranium enrichment industry has two income generation points. The first income generation point is at the level of FC TVEL and is formed at the expense of the difference between the SWU market price and the SWU transfer price (the SWU transfer price is the price for which FC TVEL buys SWU from uranium enrichment enterprises). The second income generation point is at the level of uranium enrichment enterprises and is formed at the expense of the difference between the SWU transfer price and the SWU production cost. The income made at the second point goes in part, in the form of dividends, to FC TVEL. This table presents the extreme case (the lower estimate) when the enterprise-level income is equal to zero.

[13] Investments at the shop level were considered.

In 2016, the management of FC TVEL concluded that optimization of production facilities would require the closure of the uranium enrichment plant (Isotope Separation Plant – ISP) at SCC and the transfer of generation 8th GCs to the ECP site. It was planned to implement this decision in the event of the successful year-long operation of the generation 8th GC block that was disassembled at SCC in October 2016 and commissioned at ECC in early 2017. The available data makes it possible to conclude that the R&D for and the pilot operation of the GC block transferred from SCC to ECC has been successful. In late 2018, FC TVEL decided to move all blocks of generation 8 GC from SCC to ECP (2 units in 2018 and 5 units in 2019 and 1 units in 2022). Comparison of SCC revenue under the item "conversion and enrichment products" for 2017-2021 confirms the fact that blocks were relocated in 2018-2021 and were installed at ECP site.

In 2022, a large contract was signed between EDF and TENEX for the processing of regenerated uranium of French origin (radiochemical purification, conversion, enrichment) in the period from 2022 to 2032, in which SCC plays the role of the main contract executor. The enrichment capacity of the SCC is quite sufficient to carry out the work under this contract.

Currently, FC TVEL is planning to shut down the plant after the completion of the contract, as the capacity of the plant will be significantly reduced on the reason of most part equipment life-time expired and it will not be economically feasible to continue operating a small amount of equipment that has not exhausted its resource.

Table 3.6

Actual data (2021) and planned dynamics of SCC operational capacities development in 2022-2030, mln. SWU per year

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
SCC operational capacity, mln. SWU per year	3.0	2.9	2.9	2.9	2.7	2.5	2.3	2.1	1.9	1.7

<u>JSC "Angarsk Electrolyzing Chemical Combine" development program</u>

AECC development concept up to 2030 was adopted in 2020. The AECC main direction of activity is "stable operation of separation production in the mode of additional enrichment of accumulated volumes of depleted uranium hexafluoride".

AECC business-plan and budget for 2018-2022 were approved in 2017.

Basic goals and objectives of the Angarsk Electrolyzing Chemical Complex (AECC) for 2018 thru 2022:

- ✓ Ensure a high level of process discipline for trouble-free and efficient operation of core process equipment;
- ✓ Reduce the full cost of SWU.

Table 3.7

Actual data (2021) and planned dynamics of AECC operational capacities development in 2022-2030, mln. SWU per year

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
AECC operational capacity, mln. SWU per year	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.1

In 2015, AECC switched to production of exclusively natural-grade uranium hexafluoride (0.711% of ^{235}U) from accumulated production tails. The obtained product is shipped to ECP for the production of EUP. The switchover to production of exclusively natural-grade uranium hexafluoride (0.71% of ^{235}U) from accumulated tails will make it possible for AECC to process all of the depleted uranium in storage at the AECC site approximately up to ~ 2035[20]. The depleted uranium hexafluoride left after re-enrichment (secondary tails) is delivered to ECP to be converted to uranium oxides at "W" units.

In 2016, activities were begun at AECC to decommission high-duty onsite production installations. Primarily, these include the gas diffusion plant and the conversion plant. Some of the AECC conversion plant equipment is transferred to SCC. It is planned to complete the gas diffusion plant commissioning by 2030.

The exact deadlines for the termination of the uranium activities at AECC have not been fixed. The likely timeframe for the cessation of uranium enrichment activities at the AECC is determined by the timing of main equipment service life exhausted and the completion of a number of projects at the AECC:

- ✓ The service life of the first four units of gas centrifuge equipment at AECC (GC of generation 6+) will be ~ 40 years by 2030 and it should be shut down. The 40-year resource of other blocks with GC generation 6+ will be reached only in 2035-2036, 2040-2041 and 2045-2047. The 30-year lifetime of the 8th generation GC will be reached in 2039. However, the Rosatom State Corporation's Depleted Hexafluoride Uranium Safe Handling Program suggests that by 2035 it is planned to "completely free the AECC site from nuclear materials". The authors of the report interpret this provision of the Rosatom State Corporation's DUHF Safe Management Program as the fact that by ~ 2035 uranium enrichment production at AECC should be stopped. IBR predicts that the uranium enrichment plant will be shut down by ~ 2035 due to increased costs associated with a decrease in plant capacity, as well as sufficient production at UECC and ECP;
- ✓ All of AECC's early facilities (the gas diffusion plant and the conversion plant) should be decommissioned to a green field condition".

The price of electricity for AECC is the lowest within four uranium enrichment enterprises. Therefore, for AECC it is economically viable to operate a 6+ generation GC with relatively high-energy consumption. The plant does not require financial resources for modernization. Both of these factors influence at the low cost of SWU.

3.4 Development dynamics of the Russian uranium enrichment industry planned by SC Rosatom / FC TVEL

Summing the development strategy of FC TVEL updated in 2020 and the strategies / plans for the development of Russian uranium enrichment enterprises, it seems possible to get the "official" view at FC TVEL enrichment industry development. We emphasize once again that this view does not consider the impact of the Russian-Ukrainian conflict (2022) that has begun on the development of the Russian uranium enrichment industry.

Table 3.8 presents the WNA-2021 forecast of the needs of the world nuclear power industry for uranium enrichment services until 2040, with a tails value of 0.22% ^{235}U.

Table 3.9 presents the "official" version of the dynamics of the development of the Russian uranium enrichment industry capacity and three options for using this capacity, depending on the the tails assay used both in the enrichment of natural uranium and in the additional enrichment of accumulated from past activities or imported "rich" uranium tails. In each of the options, two directions of using the capacity of the Russian uranium enrichment industry (enrichment of natural grade uranium and additional enrichment of "rich" uranium dumps accumulated from past activities or imported) are equal in total to the current (for each year) nominal operating capacity of the Russian uranium enrichment industry. The negative values of the capacity of the Russian uranium enrichment industry, intended for the re-enrichment of previously accumulated or imported "rich" uranium tails, show the magnitude of the lack of capacity in the current year for the task of re-enriching accumulated from past activities or imported "rich" uranium tails. As it was established in the previous sections, the Strategy-2020 of SC Rosatom / FC TVEL does not provide for

[20] According to General Director of AECC Igor Petrov (November 2015), the volume of accumulated depleted uranium will permit to AECC operates in "Mine" mode ~ 12-13 years (production of uranium hexafluoride, the natural quality from the accumulated depleted uranium). According to the new AECC General Director Alexander Dudin (July 2016), the accumulated depleted uranium is enough for 20 years of AECC operation in the "Mine" mode.

CHAPTER 4

STATE AND OUTLOOKS FOR THE RUSSIAN URANIUM ENRICHMENT TECHNOLOGIES DEVELOPMENT

4.1 General overview of the Russian uranium enrichment technology

A block diagram of the Russian uranium enrichment technology is presented in Figure 4.1.

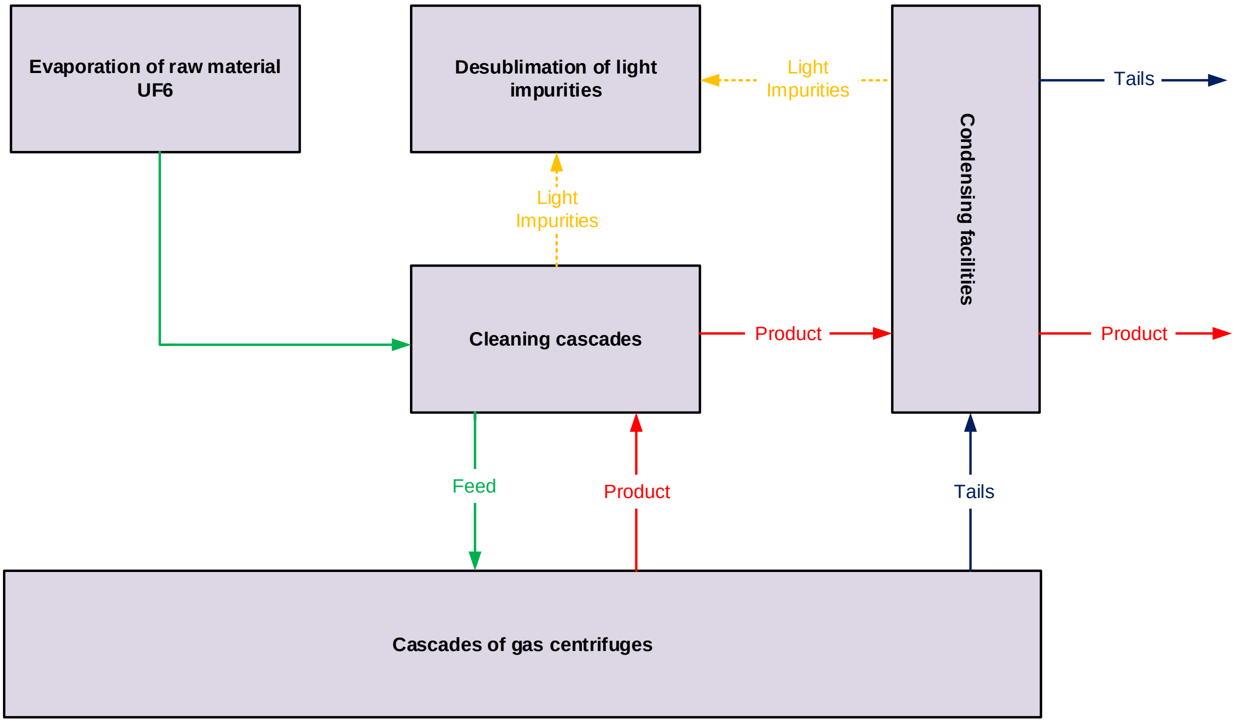

Figure 4.1
Block diagram of Russian uranium enrichment technology

Uranium hexafluoride (UF_6) delivered from sublimation production in the solid state. "Evaporation of raw materials" (Figure 4.1) is produced by induction heating of container with UF_6 in special inductors. Gaseous UF_6 enters to the purification cascade. Here, raw UF_6 is purified from impurities. Previously, gas diffusion units were used as equipment for UF_6 purification. Gas diffusion machines worked on the principle of pumping gas through special porous filters. Currently, the purification cascades consist of specially designed gas centrifuges of the OGC-200 model. In the process of purification, a "dump" is formed, which is a mixture of gases with low atomic masses and air. The gas mixture is sent for further processing to the desublimation unit, where the precipitation of the target substance and the removal of production impurities take place.

UF_6 purified from impurities enters gas centrifuge blocks, where at each stage the concentration of the 235U isotope in the product increases and, accordingly, decreases in the tails. The enrichment process in gas centrifuges is a change in the kinetic and potential energies of the gas in each stage, and an increase in the concentration of UF_6 by 235U occurs by selecting flows from points with the maximum concentration of the substance. Such physical processes are accompanied by a significant release of thermal energy. The removal of heat energy is organized in two ways: (1) by water cooling of special jackets of gas centrifuges, which are an element of their design; (2) by cooling the bodies of centrifuges and other equipment with air.

and in the maintenance and development of the site's supporting infrastructure as the whole (offsite grids, roads, security and so on).

Air cooling is carried out using ventilation systems, which are equipped with industrial premises. In addition to the function of cooling the housings of the GC, ventilation compensates for heat gains from other (electrical) equipment and provides the required humidity conditions in the room. The required air humidity prescribed by the technical specifications (TU) is a prerequisite for reliable and safe operation, since it prevents the formation of condensate on the surfaces of the equipment. The absence of condensate on the surfaces of the equipment eliminates the possibility of short circuits in electrical devices, as well as surface corrosion. The most important function of drying the air that comes into contact with the communications of gas centrifuge production is to exclude moisture infiltration into the internal cavities of equipment and communications. The technological process at almost every stage is carried out in a vacuum. Ensure absolute tightness of production, which has many kilometers communications and millions of places of detachable connections is impossible. Inevitably outside air is sucked into the internal cavities, while moisture, contained in the air, upon contact with UF6, enters into a chemical reaction: $UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$. The resulting solid substance UO_2F_2 clogs communication, interferes with the conduct of a normal technological process, and the resulting HF substance, which has significant chemical activity, causes corrosion damage to communications and equipment.

After enrichment in gas centrifuge blocks, the UF6 stream (Figure 4.1) is divided into two parts. One part - "selection" (actually product UF_6) - goes to purification cascades for purification, and then goes to condensation, where the product is condensed into commercial containers. The second part - the waste (the part of UF_6 depleted in the ^{235}U isotope) - is fed for condensation in long-term storage containers. Condensation of conditioned and tailing UF_6 is carried out by cooling the walls of the tanks with a 25% solution of $CaCl_2$. Cooling is carried out using refrigeration machines. Cooling temperature ~ 246 K. The only significant problem with brine cooling systems is high chemical activity of $CaCl_2$. Associated with this circumstance negative consequences, namely the corrosion rate of the communication metal, reaching 0.15 mm per year, it was possible to significantly reduce, to a value of 0.01 mm per year, due to the selection and introduction of corrosion inhibitors into production.

The process of condensation and purification of process streams to achieve product of the required quality is carried out at temperature levels T = 77 K, T = 193 K and consists in carrying out desublimation and sublimation of the flow UF_6 in special temperature-controlled containers. The containers are placed in cooling vessels (dewars). The desublimation unit is cooled with "cold" air (temperature T = 193 K) and liquid nitrogen (temperature T = 77 K).

During the transitional and warm periods of the year, the cooling of production facilities of separation plants is provided by refrigeration stations of significant capacity.

Formed in the fifties and eighties of the last century, the technological processes used in existing production are characterized by a high degree of safety, but at the same time they have insufficient energy efficiency, a low degree of automation, and are characterized by the use of a large share of manual labor.

4.2 Management system for the development of uranium enrichment technologies

Senior Vice President supervises development of technologies for the separation-sublimate complex (SSC) at FC TVEL for research and technical activities, technology and quality. The department immediately in charge of the development of the separation complex technologies reports to Senior Vice President:

- ✓ Department for the Implementation of the New GC Development Program.

The production process optimization problems in the Russian enrichment industry are solved within JSC “CDTI” (full name Open Joint Stock Company “Central Design and Technological Institute”), which is an integrated company consolidating the development effort subdivisions of the enterprises incorporated into Fuel Company TVEL.

The department provides short-, medium- and long-term planning and financing of R&D.

Up to the end of 2015 there were three design organizations in Russia, which were engaged in R&D and experimental development in designing GC, namely:

Table 4.1

GC 1-6 generations technical indices

GC model	VT-3	VT-3F	VT-3FA	VT-5	VT-7[22]	VT-33D	VT-33D2
GC generation	I	II	III	IV	V	VI	VI+
GC design designation		Product 128				Product 351D	Product 351D2
Year of GC commercial manufacture onset	1956	1959	1962	1964	1969	1984	~ 1990
GC output, SWU per year	~ 0.5	~ 0.8	~ 1.1	~ 1.7	~ 2.7	~ 3.6	~ 3.8
Geometrical dimensions of the rotor, height/diameter (internal/external), mm	~ 440 / ~ 114/126	~ 440 / ~ 114/126	~ 440 / ~ 114/126	~ 440 / ~ 114/126	~ 440 / ~ 114/126	~ 460 / ~ 114/126	~ 460 / ~ 114/126
Rotor rotation operation frequency, Hz	~ 650	~ 800	~ 950	~ 1,100	~ 1,350	~ 1,500	~ 1,550
Linear velocity of the internal/external rotor side wall, m/sec	~ 216 / ~ 231	~ 270 / ~ 289	~ 325 / ~ 353	~ 399 / ~ 435	~ 490 / ~ 532	~ 555 / ~ 628	~ 579 / ~ 649
Design (guaranteed)/ Forecasted / Actual life-time, years	~ 3/ - / -	~ 3/ - /~10	~ 10/ - /~12	12.5/ - /~20	12.5/35/35	15/40/36	15/40/30
The probability of failure: design / actual for guarantee resource / actual for after guarantee resource, % per year					0.2/0.2/-	0.2/0.01[23]/0.01	0.2/0.01[24]/0.01

[22] Since the second half of 1975, solely the VT-7M retrofitted 5th generation centrifuge was manufactured. Considerable outage of the VT-7 GC after two years of operation, caused by crack initiation and propagation in the GC rotor, was the reason for the retrofitting. Alterations were made in the GC design as a result of the retrofitting. Certain structural materials of the GC were also replaced. In 1980 one more retrofitting of the 5th generation GC was made, which improved the GC reliability. The retrofitting did not affect the 5th generation GC efficiency.

[23] The operator points out a very high reliability of the 6th generation GC (6 & 6+). Hence, ECP specialists in 2012 stated that throughout the long period of the 6th generation GC (6 & 6+) operation actually no GC failures.

[24] The operator points out a very high reliability of the 6th generation GC (6 & 6+). Hence, ECP specialists in 2012 stated that throughout the long period of the 6th generation GC (6 & 6+) operation actually no GC failures.

The GC's electric power supply system at 904 building ECP was based on the dynamic frequency converters up to 2018 (that have enough losses), which were located in three extensions to building 904 (high-frequency converter substations - VPP-41, VPP-42, VPP-43). In the middle of 2017, the ECP started the project implementation "Modernization of electric drivers of the high frequency electric current generators (HFECG) type VGT-1500 (HFECG-1500) with the aim to increase the main technological equipment capacity (GC of 6th generations) situated in the building 904, as the result of VGT-1500's rotor rotation frequency increasing, that (VGT-1500) is the high frequency electric power supply for GC operation". The first contract (~ 79.0 Mln. RUR (~ $ 1.3 Mln.) for six high voltage frequency converters (HVFC) purchasing and commissioning was concluded by ECP at the middle of 2017. VPP-41 work was completed in 2017. In 2018, 17 AT27-3M2-10 / 10-11S94M-K12-14 static frequency converters with a capacity of 3,150 kW each were installed in VPP-42 and VPP-43. The contract price was 214 million rubles (~ $ 3.3 million). The implementation of this project at ECP indirectly confirms the extension of the assigned resource of GCs of generations 6 and 6+ up to 40 years. The 35-year service life of the first blocks with GC of the 6th generation at ECP expires in 2023. If the lifetime of the 6th generation GC was not extended to 40 years, the implementation of this project would be economically inexpedient.

Each of HVFC has capacity 3,150 kW and operation voltage 10,000 V. HVFC is intended for frequency control of asynchronous electric motors with squirrel-cage rotor of the type 4AZT-3150/10000. The electric motors with squirrel-cage rotor of the type 4AZT-3150/10000 is using as electric drivers of high frequency electric current generators (HFECG) type VGT-1500. Within the framework of this contract, the modernization of the power supply system of all blocks equipped by 6th generation GC will be carried out. The replacement of HVFC with new ones is performed without stopping the cascades blocks. At the time when the old HVFC is replacing by new one, the power supply of GC cascade (block) was carried out by HVFC working in parallel with HVFC that was under replacement.

On the scale of ECP, the transition from the rotor working frequency of 1,500 Hz to 1,550 Hz for the 6th generation GC give an increase in the nominal power ~ 0.6 Mln. SWU per year.

<u>GC of 7-th and 8-th generations</u>

On January 18, 1984, the USSR Ministry of Medium Machine-Building Industry (Minatom) took a decision to focus on the development of the 7th generation GCs based on the design version proposed by the UEIP (Urals Electrochemical Integrated Plant). Conducting (in conjunction with the Central Plant Laboratory) long-term life tests of aggregates and many supercritical centrifuges NGC-85, developed by OKB GAZ was carried out in 1985-1986. Tests of the industrial prototype of the 7th generation GC were carried out in 1985-1986. In 1991, tests of the pilot lot of the 7th generation GC were launched. In November 1995, the Acceptance Board recommended serial production of the 7th generation gas centrifuges. Starting from 1996, Russian machine-building enterprises produced subcritical GCs of the 7th generation designated as "Product 343" or VT-25. On July 31, 1997 the UEIP commissioned the first unit equipped with the 7th generation GCs.

In May 1999, Minatom approved a plan aimed at the development of the 8th generation gas centrifuges – PGTs-8. In September 2003, the Acceptance Board recommended launching batch production of those centrifuges. On July 13, 2004, the first unit of PGTs-8 gas centrifuges was put into operation.

The design of the 7th and 8th generation GC was based on the use of improved structural materials in the GC rotor design, GC improved magnetic suspension and a GC drive new electric motor. The 7th and 8th generation GC rotor was made of an aluminum rotary bed of the V96Ts alloy (the same as alloy "1960") ~ 3.8 mm thick reinforced with fiber glass filament, carbon fiber and Armos aramid filament base composite materials. The rotor wall total thickness is ~ 5-6 mm. Aluminum alloy V-95 was used in the design of end pieces and GC molecular seals. The 7th and 8th generations of GCs differ only in the quality of the rotor structural materials, which allows raising the rotor frequency in the Gen 8 gas centrifuges by 150 Hz vs. the Gen 7 rotor.

Since 2004, the Russian mechanical engineering enterprises are engaged in batch manufacture of subcritical 8th generation GC, its designation "Product 356" or PGC-8.

The Novouralsk Research and Design Center design bureau is the main designer of the 7th and 8th generation GC (the design documentation and specifications for the 8th generation GC were approved in 2004, in the same year manufacture of the 8th generation GC was started).

Table 4.10

Generation 9+ GC test schedule

Designation of test batch	Dates of testing	Number of assemblies/GCs in test batch	Notes
	2011-2012		Testing of individual GC prototypes of different designs.
Pilot batch 1 (PB-1)	2013	~ 6 assemblies / ~ 120 GCs	Testing of prototypes of different designs as part of the assemblies.
Pilot-industrial batch 1 (PIB-1)	Manufacturing – September 2014. Installation of assemblies – October-November 2014. Commencement of operation – November 2014.	~ 102 assemblies / ~ 2,040 GCs	Assemblies installed into section No. 2 of block/unit 21 at UECC's production shop No. 53. Operation successful. No reliability claims.
Pilot-industrial batch 2 (PIB-2)	Manufacturing – September 2015. Installation of assemblies – October-November 2015. Commencement of operation – November 2015.	~ 128 assemblies / ~ 2,560 GCs	PIB 2's GC assemblies installed into section No. 3 of block/unit No. 21 at UECC's production shop No. 53. As of mid-2016, no GC failures have been recorded.
Pilot-industrial batch 3 (PIB-3)	Manufacturing – 1st quarter of 2016. Installation of assemblies – 2nd quarter of 2016. Commencement of operation – 3d quarter of 2016.	~ 128 assemblies / ~ 2,560 GCs	Assemblies installed into section No. 4 of block/unit No. 21 at UECC's production shop No. 53. The operation of OPP-2 and OPP-3 was recognized successful. A decision was made to start the commercial production of the new GC beginning at the end of the 1st quarter of 2017.

Table 4.13

The list and characteristics of structural materials supplied to the Russian and foreign GC industry for GC rotor manufacture

Title	Titer, tex	The breaking load of a complex filament thread (fiber tow) in tension, N	The specified breaking load of a complex filament thread (fiber tow) in tension, GPa	Modulus of elasticity, GPa	Density, g/cm^2	Manufacture	GC generation (material application)
High-duty fibers							
Aramid fiber thread Armos 58.8A (RUSLAN-VM type)	58.8	118	4.5	137	1.50	JSC Kamenskvolokno	6/7/8/9
Glass fiber thread VMPS6-14.4x4Z100-78	57.6	96	4.2	95	2.46	JSC SPA Stekloplastik	9
Glass fiber thread VMPS8-27x4Z100-4C	112.0	182	4.2	95	2.46	JSC SPA Stekloplastik	6/7/8
Carbon fiber UKN-5000	410.0		2.5	210±30	1.71±0.04	UMATEX Group (JSC Chimpromengineering)	8
Carbon fiber VMN – 4MS1 & GZ – 23/360K						UMATEX Group (JSC Chimpromengineering)	9
Carbon fiber TS 36S-24K 1600 tex	1600		4.9	250	1.81	Formosa Plastics Corp. (Taiwan)	9+
Carbon fiber T800HB-12K-40B / T800HB-12K-50KB	445		5.5	294	1.81	Toray Carbon Fibers Europe S.A.	9+
Carbon fiber TENAX®-E IMS65	830		6.0	290	1.78	Toho Tenax Europe GmbH	9+
Carbon fiber H3055S-12K	725		5.5	290	1.80	Hyosung corporation (S.Korea)	9+
Carbon fiber UMT45-12K-EP / UMT49SA-12K-EP	790 / 770		4.5 / 4.9	255 / 260	1.78	UMATEX Group (JSC Chimpromengineering)	9+
Basalt fiber twisted BS 10–90x2Z75-KV-12	90		9.0			Basalt Materials LLC	9+/11
High-module fibers							
Carbon fiber tow VMN-4MTI	520±50	98	Not regulated	450	1.85	UMATEX Group (JSC Chimpromengineering)	7/8
Carbon fiber tow VMN-4MTI-2 or VMN-4MTS	530±50	98	Not regulated	450	1.80	UMATEX Group (JSC Chimpromengineering)	7/8
Carbon fiber tow UMT430-12K-EP	700±50		Not regulated	430	1.84	UMATEX Group (JSC Chimpromengineering)	11

In 2021, the price of supplies of Russian carbon materials used for the production of HC 9+ was:

- ✓ Carbon fiber UMT45-12K-EP – $ 26 per kg (without VAT);
- ✓ Carbon fiber UMT49SA-12K-EP - $ 35 per kg (excluding VAT).

Table 5.1

Comparison of specific investment expenses of the URENCO and FC TVEL technologies

Capacity development options	Technology			
	Replacement TC-12 by TC-12	Replacement TC-21 by TC-21	Replacement GC-5/6/7/8 by GC-9+	Replacement GC-5/6/7/8 by GC-11
Upgrading (FC TVEL)	-	-	168	~ 107 (Estimation)
Upgrading (URENCO, royalty-free), $/SWU	335	244	-	-
Upgrading (URENCO, including royalties), $/SWU	382	291	-	-
	Technology			
	TC-12	TC-21		
New Construction (URENCO, royalty-free), $/SWU	405 / 479	283 / 311	-	-
New Construction (URENCO, including royalties), $/SWU	451 / 525	328 / 359	-	-

Notes:

- ✓ Data on the specific investments in the development of URENCO's industry has been taken from the IBR report ETC TECHNOLOGICAL PLATFORM / URENCO & AREVA STATE & DEVELOPMENT FORECAST, 2020.
- ✓ Currency exchange rates used or conversion: EUR 1.00 = $ 1.18; RUR 74.0 = $ 1.0 (the average exchange rates of $, EUR and RUR in the middle of 2021 were used).
- ✓ URENCO and ORANO (AREVA) perform an annual royalty payment to ETC for the use of the technology. Royalties are included in URENCO's operating costs. For URENCO, for the purpose of comparison with specific investments with Russian technologies, one of the options is calculation of specific investment costs (specific overnight cost), considering Royalties recalculation into investment costs.
- ✓ The New Construction data given with "/" is respectively for the construction of new facilities using respectively frame buildings and reinforced-concrete buildings.

Table 5.2

Comparison of the specific operating expenses of the URENCO and FC TVEL technologies

	Company	
	UECC and ECP	URENCO
Specific operating costs (2021), $/SWU per year	~ 9-10	~ 38

Notes:

- ✓ Currency exchange rates used or conversion: EUR 1.00 = $ 1.18; RUR 74.0 = $ 1.0 (the average exchange rates of $, EUR and RUR in the middle of 2021 were used).

As can be seen from the data in Table 5.1, the specific investments in the development of Russian enrichment industries based on the GC 9+ technology are lower at the present time (2020) (the development is based on upgrading), as compared to the specific investments in the development of URENCO's enrichment industry (at the present time the development is based on new construction (USA) and the upgrading (Europe)). With the transition to upgrading on the base of the 11th generation GC technology, the advantage of FC TVEL over URENCO, in terms of specific investments, will be even more significant. The advantage of FC TVEL over URENCO in terms of the specific operating costs per SWU looks convincing too as for the specific investments per SWU.

It should be however that both Russian industry for production of enrichment equipment and uranium enrichment companies have managed to achieve such an impressive result (in a dollar expression) largely thanks to two times drop in the ruble exchange value against US dollar in 2014-2015. In 2019-2020, another significant fall of the ruble to the dollar occurred. The role of other factors in the decrease in the specific investment and in the specific operating costs per SWU in terms of $ is smaller but, still, exists. The decrease in the specific investment costs per SWU was achieved, among other things, through improving the design of generation 9+ GCs and making them cheaper as compared to GCs 9,

APPENDIX 4

PROSPECTS FOR PROCESSING AND LIQUIDATION OF DEPLETED URANIUM HEXAFLUORIDE (DUHF) STOCKS

To date (2020), since the beginning of the development of the nuclear industry, more than 2 million tons of DUHF have been accumulated in the world, including over 1 million tons[71] in Russia.

In 2015, the updated Concept for the safe handling of DUHF (hereinafter - Concept-2016) was adopted. In order to further implement the Concept-2016, the Rosatom State Corporation's Program for the Safe Management of DUHF was developed (hereinafter - Program-2020), which defines the horizons and outlines a roadmap for solving the problem of the complete elimination of DUHF stocks accumulated at TVEL FC enterprises. For industrial processing of DUHF and its transfer into a safe form, the W-ECP unit with a capacity of 10 thousand tons per year is currently used at the site of the ECP. At the next stage of processing the accumulated stock of DUHF, the defluorination units will be replicated. It is planned that in 2024 one more unit will be put into operation - W2-ECP at the site of PA ECP, which will increase the processing capacity to 20 thousand tons of DUHF per year, and by 2028 at the same enterprise it is planned to increase the capacity of installations up to 30 thousand tons per year (project W3-ECP). In addition, a W-UECC unit with a capacity of 20 thousand tons of DUHF per year will be commissioned at the UECC site. At the SCC site in 2025, an NHP-SCC unit with a planned capacity of up to 12 thousand tons of DUHF per year will be put into operation. The technology of flame defluorination of DUHF, which is being developed for this unit, should be tested and implemented by 2025. If the flame defluorination technology is not introduced at the NHP-SCC unit, then it is planned to increase the capacity of the W-UECC unit to 30 thousand tons of DUHF per year. An important decision, which was approved by the 2020 Program, is the decision to reduce the number of sites with DUHF stocks. First of all, it is planned to vacate the AECC site by 2035 by transferring all DUHF stocks to the site of the ECP. Until 2040, the site of the Siberian Chemical Combine will be vacated. Thus, considering the commissioning of the five above-mentioned units (W + NHP-SCC), the liquidation period of the DUHF warehouse at all sites of the TVEL fuel company will be 35 years, that is, until 2057. Table A.4.1 shows the main activities that must be performed to solve the problem of complete elimination of DUHF stocks at all sites[72].

[71] Depleted uranium hexafluoride (current situation, issues of safe handling and prospects), ERC Bellona.
[72] Rosatom State Corporation's DUHF Safe Handling Program, 2019

Table A.4.1

The main activities for the implementation of the program for liquidation of DUHF stockpiles

Direction	Implementation period	Expected Result
1. Expansion of DUHF processing projects		
1.1. Increasing the capacity of the W-ECP unit to 20,000 tons of DUHF per year (W2-ECP project)	2017-2023	Increase in the rate of DUHF processing, transition from accumulation to a decrease in DUHF storage Full satisfaction of the needs of FC TVEL in anhydrous hydrogen fluoride Reducing unit costs for DUHF processing
1.2. Creation of a unit for defluorination of DUHF at UECC with a capacity of 20,000 tons of DUHF per year (W-UECC project)	2020-2026	
1.3. Increasing the capacity of the W-ECP unit to 30,000 tons of DUHF per year (W3-ECP project)	2020-2028	
2. Reducing the number of DUHF storage sites		
2.1. Transfer of DUHF from the AECC site to the site of the ECP	to 2035	Complete release of the AECC site from nuclear materials
2.2. Movement of DUHF from the site of the Isotope Separation Plant (ISP) of the Siberian Chemical Combine to the sites of the ECP / UECC	to 2038	Complete exemption of the site of the Isotope Separation Plant (ISP) of SCC from nuclear materials
3. Ensuring long-term safe storage of DUHF		
3.1. Operation and improvement of monitoring systems, condition control and handling of packaging sets (PS) for DUHF, including the handling of defective PS identified during storage	constantly	1. Safe storage of containers with DUHF has been ensured for 80 years or more 2. Improved technologies for processing DUHF into safe storage forms
3.2. Implementation of current and prospective R&D in the field of safe handling of DUHF,	constantly	
including: - development and testing of the design of a protective container for moving DUHF with a long storage period over long distances; - development of a technology for preparation of containers with DUHF with a long shelf life for transportation over long distances	2019-2021	1. Developed, manufactured and tested a protective container for moving DUHF with a long shelf life 2. A technology has been developed for the preparation of containers with DUHF with a long storage period for transportation over long distances

Rosatom State Corporation recognizes that the costs of processing DUHF at W-type units (even considering the positive economic effect from the sale of fluorinated products and savings on the manufacture of containers for DUHF) exceed the costs of its storage. As a result, the operation of production facilities W in the next decade is costly and, as declared by FC TVEL, has an exclusively ecological focus. TVEL FC believes that there is an opportunity to improve the design of packaging sets and optimize storage technologies for depleted uranium oxide. This will provide additional savings in storage costs for depleted uranium. If depleted uranium is used in the future as a feedstock for fuel intended for fast reactors, these costs can be offset by the price of this feedstock. Today, the costs of ongoing work on the safe handling of DUHF are included in the cost of production of the enrichment plants of FC TVEL.

Analysis of processed and planned for processing volumes of depleted uranium hexafluoride

Table A.4.2

Analysis of processed and planned for processing volumes of depleted uranium hexafluoride

	Facility	Facility capacity, tonn UF6/year	Analised years of operation	Facility processed amount for period, tonn UF6
	W1-ECP	10 000	2009-2057	480 000
	W2-ECP	10 000	2023-2057	340 000
	W3-ECP	10 000	2028-2057	290 000
	W-UECC	20 000	2026-2057	620 000
	NHP-SCC/W-UECC	10 000	2025-2057	320 000
	Total, in UF6			2 050 000
(1)	**Total, in U**			**1 386 072**
(2)	Total, depleted U accumulated till 2022 (processed and unprocessed), tonn U			678 000
(3)	Additional depleted uranium that planned to be accumulated in 2022-2057 (Difference between (1) and (2)), tonn U			708 072
(4)	**Average per year amount of depleted uranium that planned to be accumulated in the period 2022-2057 ((3) to divide at 36 years), tonn/year**			**19 669**

With an average volume of annually generated depleted uranium ~ 19.669 tU, the feed should be ~ 22.870 tU with a ^{235}U content in the tails of ~ 0.11%. Enrichment of such a quantity of natural uranium with tails of ~ 0.11% ^{235}U requires ~ 31.3 million SWU annually. In the time period 2022-2040, the average annual capacity of the Russian uranium enrichment industry, intended for the enrichment of natural quality uranium (according to the variant of FC TVEL, interpreted by IBR) is ~ 29.3 million SWU. Then, in the time interval of 2041-2057, the average annual capacity of the Russian uranium enrichment industry should be ~ 33.6 million SWU per year. These estimates are very approximate, because a number of initial data are very estimated. However, considering two things:

- ✓ According to the State Corporation Rosatom, after 2040, a two-component era will come in the nuclear power industry (fast and thermal neutron reactors), which means at least a slowdown in the growth of demand for EUP;
- ✓ In the option of SC Rosatom / FC TVEL for the development of the uranium enrichment industry, its nominal capacity will reach ~ 34.0 million SWU per year by 2040,

we can say that the average annual nominal capacity of the Russian uranium enrichment industry is ~ 33.6 million SWU per year in the period 2041-2057, looks quite realistic.

This leads to another important conclusion. SC Rosatom / FC TVEL do not plan to import depleted uranium of foreign origin, because the existing and planned capacities for the deconversion of depleted uranium are insufficient and do not correspond to the set task of reducing to zero the balance of accumulated and generated depleted uranium and the capacities for its deconversion. Of course, this does not exclude the unlikely option of importing foreign depleted uranium to Russia for re-enrichment and exporting secondary tailings back. But, this option looks doubtful.