Russia's nuclear fuel cycle: An industrial perspective

An overview of policies, plans, and experience in producing and reprocessing nuclear fuels, and in the utilization of plutonium

by
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From the very beginning, the development of nuclear power in the former Soviet Union was based on a closed fuel cycle. Plans included the reprocessing of spent fuel from nuclear power plants, and the recycling of recovered uranium and plutonium in newly fabricated fuel elements. For the most part, this policy has not changed, and today it encompasses a new generation of reactors whose construction is being planned.

In Russia and countries of the Commonwealth of Independent States (CIS) and Eastern Europe, nuclear fuel-cycle services currently are required for 62 nuclear power plants operating with reactors that were designed in the former Soviet Union. Forty-five of these are pressurized-water reactors known as WWERs. Of these, 19 are WWERs having an electrical generating capacity of 1000 megawatts and 26 are WWERs having a capacity of 440 megawatts. The remaining operating plants include 15 channel-type, graphite-moderated reactors known as RBMKs and two fast-breeder reactors known as BNs.

This article reviews Russia's nuclear fuel cycle industry from a technical and industrial perspective. It specifically focuses on reprocessing experience and plans, the fabrication of fuel for WWER, RBMK, and fast reactors; the management of spent nuclear fuel; and the current situation and prospects for using mixed oxide (MOX) fuel in Russia's nuclear power reactors.

Reprocessing of nuclear fuel

The reprocessing option is followed for the spent fuels of all WWER and BN reactors, but not for RBMKs, whose spent fuel is placed in storage.

The decision not to reprocess fuel from RBMK-1000 and RBMK-1500 reactors was taken largely for economic reasons. Reprocessing would be uneconomical because of the fuel's low content of fissile isotopes of uranium and plutonium. Spent fuel from RBMK reactors is placed in sealed canisters and stored in facilities at the nuclear plant site having a capacity of about 2000 tonnes heavy metal (tHM).

For other types of fuels, one reprocessing plant is operating and another one is being built.

● **The RT-1 plant in Chelyabinsk.** Located at the "Mayak" complex, this plant was commissioned in 1971 and intended for reprocessing fuel from WWER-440 reactors, fast reactors, and the propulsion reactors of ice-breakers and submarines. The plant's capacity for the main type of fuel (WWER-440 fuel) is 400 tHM per year. It operates with an aqueous extraction technology using tributyl phosphate with a hydrocarbon diluent. The process takes places in multistage extractors with mechanical and pulsed mixing of phases. The clean-up factor for high fission products is between 10^6 and 10^9, which ensures that pure uranium and plutonium, as well as neptunium, are produced. The technology also allows extraction of strontium-90, caesium-137, technetium-99, and other radionuclides from the spent fuel.

Once reprocessed, the uranium is returned to fuel-element production. The final uranium product of the plant is a fused cake of uranyl nitrate hexahydrate with the required uranium-235 enrichment. The fused cake is obtained after mixing and concentration of the uranium re-extract and a solution of highly enriched uranium. The adjustment of the solution for correct enrichment also can be done at the Ust-Kamenogorsk plant in Kazahkstan, where the fuel pellets are made. Currently, most of the fused cake obtained at RT-1 has a uranium-235

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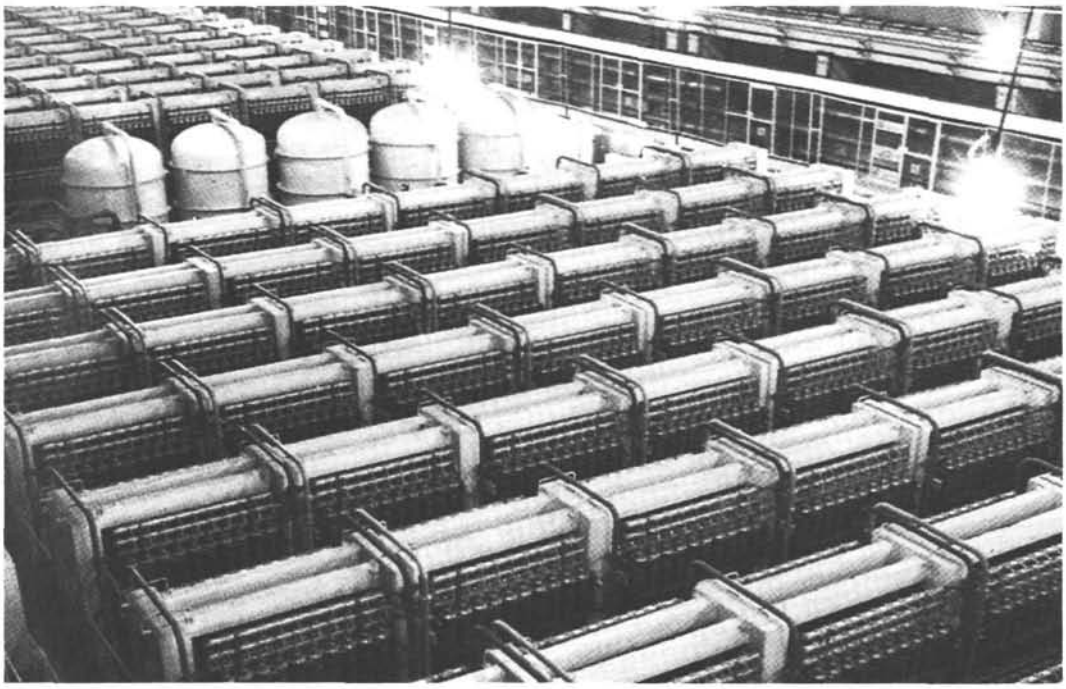


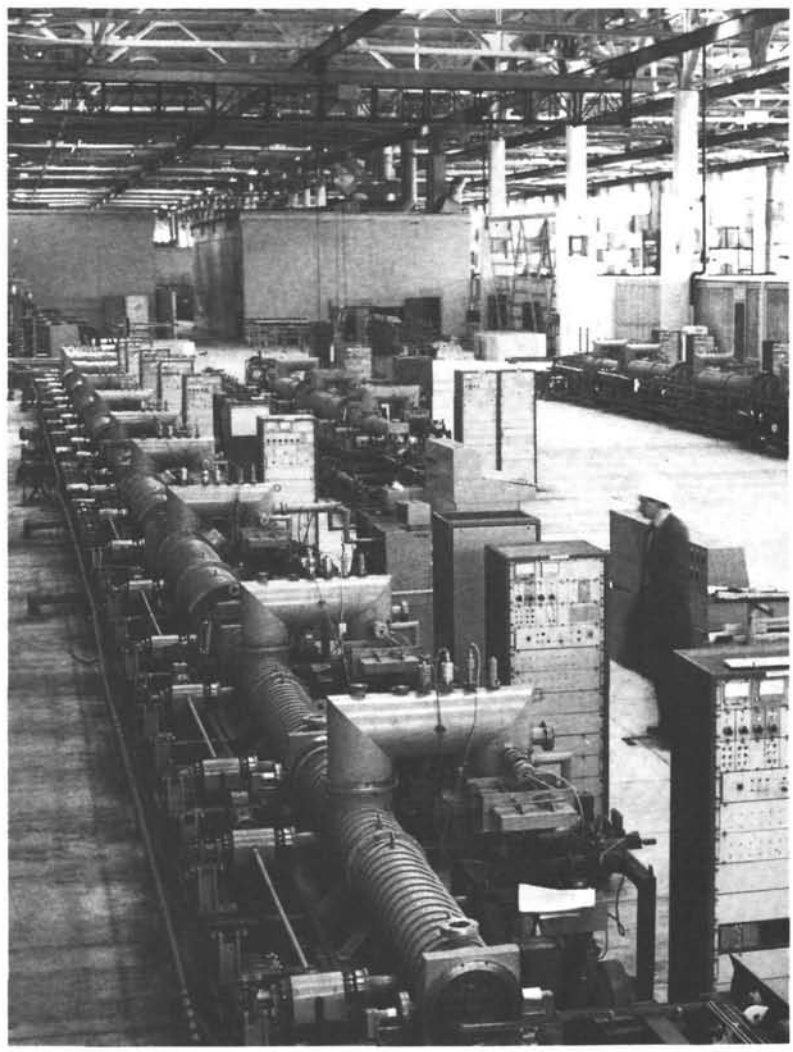
Below: The automated production line for WWER-440 fuel assemblies at the Electrostal fabrication plant near Moscow. *At left:* Centrifuges at the uranium enrichment plant at Krasnoyarsk. *(Credit: Minatom, Russian Federation)*

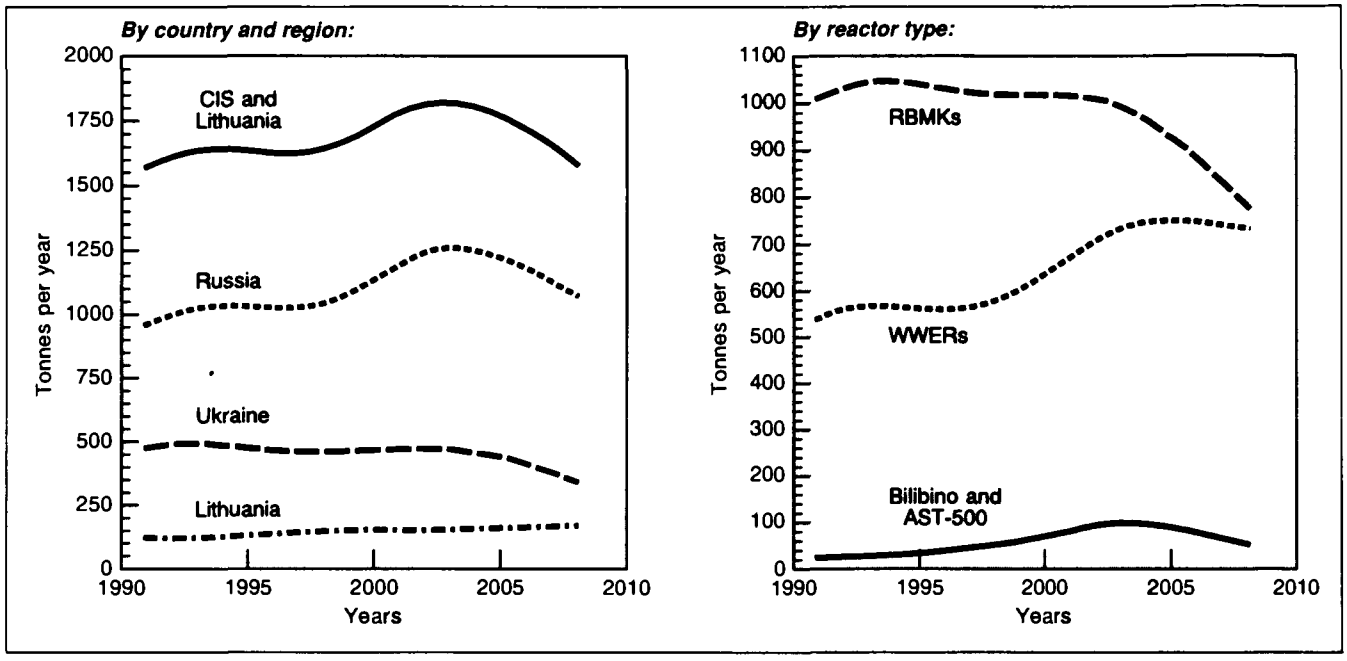
content of 2% to 2.5% and is used to make fuel pellets for RBMK-1000 reactors. Work now is being done to include reprocessed uranium in the fuel cycle of the RBMK-1500 reactors at the Ignalina nuclear power plant in Lithuania and in the fuel cycle of BN- and WWER-type reactors. Plutonium obtained at RT-1 is temporarily stored on site in dioxide form.

● **The RT-2 plant, under construction at Krasnoyarsk.** This plant, which is being built to reprocess nuclear fuel from WWER-1000 reactors, is scheduled to come on stream in lines. The first line will be able to reprocess up to 1000-to-1500 tHM per year of spent fuel from WWER-1000s. Like at RT-1, the final uranium product will be a fused cake of uranyl nitrate hexahydrate. It will first go to uranium hexafluoride production and then to uranium enrichment. Until the first line is commissioned, spent fuel from WWER-1000 reactors will be stored in the a central facility at RT-2 that already has been built. This facility has a design capacity of 6000 tHM and will be fully packed by the year 2005. Storage capacity presently is 3000 tHM.

Fuel enrichment and fabrication

The demand for nuclear fuel to supply WWER-type plants currently determines the required volume of industrial fuel element production. *(See graphs.)* All these reactors use enriched uranium (Russia has no reactors operating on natural uranium).





Fuel requirements for water-cooled reactors, 1990-2010

A number of uranium enrichment and fuel fabrication plants are operating.

● **Enrichment plants.** The first uranium enrichment plant in Russia started operation in 1949 in Sverdlovsk. Three further plants came into operation later at Tomsk, Angarsk, and Krasnoyarsk. The method used in all four uranium enrichment plants was the gaseous diffusion method. Development of an innovative enrichment method using gas centrifuges started in the early 1950s. The world's first industrial plant equipped with gas centrifuges came into operation in 1964 in Sverdlovsk. Gas centrifuges were then also introduced in the other three plants. The transition to gas centrifuges meant that the separation capacity of the plants increased by a factor of 2.4 while at the same time electricity consumption was reduced by a factor of 8.2. Nowadays fifth-generation gas centrifuges are used in serial production. The specific energy consumption of this centrifuge model per separative work unit is 25 times less than with the gaseous diffusion process.

In the enrichment process, two methods can be employed to obtain the uranium hexafluoride used to enrich the uranium — direct fluorination of uranium oxides with gaseous fluorine or fluorination of uranium tetrafluoride. Both methods are used in Russia. Economically speaking, the second method is the more attractive since less expensive gaseous fluorine (by a factor of three) is required. In both cases, the processes are exothermic and great quantities of heat are released, with extremely high temperatures developing in the reaction vessel. When designing equipment for these processes, therefore, particular attention must be paid to the removal of heat and to the choice of material for the reaction vessel.

Industrial nuclear fuel and cladding production

Plant	Type of production		Annual capacity (tonnes)	Production in 1992 (tonnes)
	Reactor	Final product		
Electrostal (near Moscow)	WWER-440 RBMK BN BN	fuel assemblies fuel assemblies fuel for reactor core fuel for reactor breeding blanket	700 570 20 15	230 570
Novosibirsk	WWER-1000	fuel assemblies	1000	210
Ust-Kamenogorsk (Kazakhstan)	WWER RBMK	fuel pellet	2650	220 570
Glazov	WWER RBMK	zirconium alloy tubing	2000 6000 km/a (tubing)	2000 km/a (tubing)

● **Fuel fabrication facilities.** Industrial fabrication of fuel elements, fuel assemblies, and fuel pellets is carried out at three plants: two in Russia (Elektrostal and Novosibirsk) and one in Kazakhstan (Ust-Kamenogorsk). Elektrostal produces fuel elements, assemblies, and pellets for WWER-440, BN-350 and BN-600 reactors. It also produces fuel elements and assemblies for RBMK-1000 and RBMK-1500 reactors using fuel pellets supplied from Ust-Kamenogorsk. The Novosibirsk plant manufactures fuel elements and assemblies for WWER-1000 reactors. Fuel pellets for the WWER-1000 fuel elements are supplied from Ust-Kamenogorsk. Zirconium production and the manufacture of articles made of zirconium-based alloys take place in Glazov (Udmurtia, Russian Federation).

Two methods are used to convert uranium hexafluoride into uranium dioxide. The plant at Elektrostal employs the flame spraying process, which is one of the gaseous or "dry" methods. The uranium dioxide powder obtained using this technology is not sufficiently free-flowing and so undergoes further treatment to obtain what is known as press-powder, a powder from which pellets are pressed.

At Ust-Kamenogorsk in Kazakhstan, where the bulk of Russia's fuel pellets are fabricated, uranium hexafluoride is processed into uranium dioxide using the ADU-process. This process involves hydrolysis of uranium hexafluoride, precipitation of ammonium polyuranate, drying, calcination, and reduction to uranium dioxide. The fused cake from the RT-1 plant serves as the raw material for fabrication of the fuel pellets for RBMK fuel elements.

Fabrication of mixed oxide (MOX) fuel

Plant/Facility	Reactor	Annual capacity	Production in 1992
"Paket" at Mayak, Chelyabinsk	BN-350 BN-600	10-12 FAs 300 kg MOX	4 FAs 100 Kg MOX (about 20% Pu)
"Paket" (modified) since 1993	BN-600	40 FAs 1 tonne MOX	
Facility at RIAR (Dimitrovgrad)	BOR-60 BN-600	1 tonne MOX (vibropack)	600 kg MOX
Plant at Chelyabinsk complex (50-60% complete)	BN-600 BN-800 (WWER-1000)	60 tonnes HM	
Plant in Krasnoyarsk	WWER-1000	planned for future	

Note: FA= fuel assembly HM = heavy metal

Management of spent nuclear fuel

While the closed fuel cycle has a positive side, namely the possibility of re-using the uranium and plutonium recovered from spent fuel, it also has a negative side: the generation of considerable amounts of high-level radioactive waste (HLW). The half-life of some nuclides is many thousands of years. For this entire period they must be kept reliably contained and prevented from coming into contact with the environment.

A deciding factor for reliable disposal of radioactive waste is the choice of a matrix material having sufficient chemical stability to contain solidified waste. Such materials include phosphate and borosilicate glass and mineral-like materials. The merit of these materials is their high resistance to leaching of the elements contained within them.

Russia has opted for vitrification. The first pilot industrial facility for HLW vitrification went into operation in 1987 at the RT-1 plant. The process took place in a ceramic reaction vessel. Water-cooled molybdenum rods positioned appropriately in the vessel served as electrodes. This facility processed some 1000 cubic meters of actual HLW, producing 160

Reprocessing and spent fuel management in Russia

Facility	Reactor	Capacity	Product
RT-1 reprocessing plant at Mayak complex in Chelyabinsk (since 1971)	WWER-440 Fast and transport reactors	400 tonnes heavy metal/annum (tHM/a)	Reprocessed uranium returned to fuel fabrication for RBMK Plutonium stored in dioxide form
RT-2 reprocessing plant in Krasnoyarsk	WWER-1000	1st line: 1500 tHM/a 2nd line: 1500 tHM/a Total: 3000 tHM/a	Reprocessed fuel will be returned to fuel fabrication for WWER and BN.
Storage facilities at each RBMK nuclear power plant site	RBMK	2000 tHM	
Storage facility at RT-2 plant	WWER-1000	6000 tHM (3000 tHM in operation)	

Note: The RT-2 reprocessing plant is under construction; the date for completion is still under discussion.

tonnes of glass blocks containing approximately 4 million curies, before operation of the furnace was discontinued in 1988.

In 1991, a new electric furnace having a capacity of 500 liters of solution per hour started operation at the same complex. Several of the shortcomings of the first furnace were taken into account in its development. To date, approximately 5000 cubic meters of liquid HLW have been processed in the new furnace, producing some 900 tonnes of phosphate glass with a total incorporated radionuclide activity of about 135 million curies.

The problems associated with the reprocessing and reliable disposal of radioactive waste would be greatly reduced if a way could be found to sort the radionuclides in advance according to their half-lives, toxicity, and possible usefulness. Much work is now going into achieving this goal.

In addition to the HLW produced at nuclear fuel cycle facilities, immeasurably greater quantities of low-level liquid waste are formed. Radioactive water at nuclear power plants and radiochemical facilities is purified by filtration, evaporation, ion exchange, and other means. The solutions are purified to the point where they can be recycled. The concentrates and intermediate-level liquid wastes formed in the process are either stored in special tanks or solidified. Several nuclear power plants already have facilities for solidifying liquid waste by the bituminization method.

By the year 2000, all operating nuclear power plants and all those scheduled for decommissioning in Russia must have built facilities for solidifying and subsequently storing liquid waste.

Plutonium utilization in nuclear fuels

Russia started work on the use of plutonium as a nuclear fuel in the late 1950s. In 1957, a core made of metallic fuel (plutonium alloy) was manufactured for the IBR-30 pulsed reactor. In 1959, the BR-5 sodium-cooled fast reactor was commissioned at the Power Physics Institute, Obninsk. It used plutonium dioxide fuel and had an overall core charge of about 150 kg. The same type of fuel was used in 1965 for the core of the IBR-2 pulsed reactor, which weighed around 120 kg. Both pulsed reactors are still operating at the Joint Nuclear Research Institute, Dubna.

These activities were not part of any broader programme but were individually commissioned projects. Systematic research on plutonium fuel began in 1970. Tests were carried out in the BOR-60 and SM-2 reactors at the Scientific Research Institute for Nuclear Reactors, Dimitrovgrad. During the first stage of this research, mechanical mixing of uranium and plutonium oxides was the main technique used to produce the fuel. A fairly large number of fuel elements was manufactured using this technique. Reactor tests were carried out to evaluate the influence of many factors on the performance of these fuel elements. Some assemblies achieved burnup rates of up to 20% with no impairment of fuel element integrity.

The positive and stable test results obtained with the MOX fuel in the BOR-60 reactor were followed up with more extensive tests in the industrial-scale BN-350 (Kazakhstan) and BN-600 reactors.

The fuel cycle for BN-350 and BN-600 reactors was initially planned to use uranium oxide fuel, which is certainly not ideal for breeder reactors. A complete conversion of these reactors to MOX fuel is not possible owing to their design and physical features. However, these reactors can be used for testing up to 25-to-30 fuel assemblies containing uranium-plutonium oxide fuel.

For this purpose, a pilot industrial facility called "Paket" was set up at the Mayak complex in Chelyabinsk capable of manufacturing up to 10 fuel assemblies per year for these reactors. The same structural materials were used as for uranium fuel (namely, austenitic steels for the fuel element cladding and ferritic martensitic steels for the six-sided cans). In the BN-350 and BN-600 reactors, a burnup rate of 9% to 11% of heavy atoms was achieved. There was no loss of integrity in any of the fuel elements. Tests performed on the fuel elements after they had been removed from the reactor showed that they had not reached the end of their useful lives.

Work on this type of fuel was given an added impetus when the decision was taken to build BN-800 reactors designed to use MOX fuel in Russia (at the South Urals and Beloyarsky nuclear power plants). At the Mayak complex, a project was started for the design and construction of a plant which would produce MOX fuel and fuel assemblies for these reactors and for the BN-600. Particular emphasis was placed on radiation safety both in the plant itself and in the surrounding area. This meant minimizing operations which generated dust. One of the most important of these is the mechanical mixing of the oxides. Therefore, work began on the development of other processes for producing MOX fuel which generated less dust. The first of these was a sol-gel process producing

granulated MOX fuel which was then pressed into pellets. This technique was used to manufacture several experimental fuel assemblies which were successfully tested in the BN-350.

However, the manufacture of the pellets from granules obtained by the sol-gel process involves a number of difficulties which make it impossible to achieve a high and stable pellet quality. Therefore, in parallel, the technique of ammonia co-precipitation of uranium and plutonium using surfactants was developed. This technique produces irregularly shaped granules which generate little dust and can be easily worked into pellets meeting the required standard. Twelve fuel assemblies were made for the BN-600 using this technology. Most of these have already been removed from the reactor following lifetime tests, and the remaining ones are being irradiated.

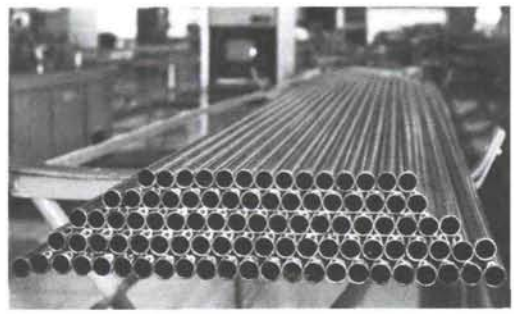
As an alternative to this technique, carbonate co-precipitation of uranium and plutonium is being investigated. No reactor tests have been performed as yet on fuel produced using this method. Another technique for producing MOX fuel — plasmochemical denitration of a mixture of uranium and plutonium nitrate solutions — is still in an early stage of research.

All five techniques mentioned above have the same aim: the production of pellets for fuel elements. However, Russia is also conducting a significant amount of research into vibro-compacted fuel elements based on granulated fuel produced using various techniques. In particular, the Scientific Research Institute for Nuclear Reactors in Dimitrovgrad has developed an electrochemical technique for co-precipitation of uranium and plutonium oxides. After the cathode precipitate has been processed and reduced to a fine powder, it is divided into six fractions graded according to particle size. The powder is then loaded into the fuel element cladding and compacted in a vibration machine. A high mean fuel density can be achieved in the fuel element by controlling the ratio of the fractions.

Up to now, all the fuel elements which have been loaded into the BOR-60 have been manufactured using this technology. In addition, two fuel assemblies have been tested in the BN-350 and six in the BN-600.

Plans and prospects

Over the past decades, a sufficiently large amount of work has been carried out to envisage undertaking the industrial-scale development of MOX fuel fabrication technology. Work on the construction of a plant to produce this type of fuel, which had been suspended, is now being resumed with a view to supplying the BN-800 and BN-600 reactors with uranium-plutonium fuel. It is estimated that this plant is 50% to 60% complete, so it will take several years to finish it.



Tubes for nuclear fuel elements at the Glazov plant. ***(Credit: Minatom)***

For the immediate future, therefore, it is planned to reconstruct the "Paket" pilot industrial facility and increase its output to 40 fuel assemblies per year for the BN-600. A similar quantity of fuel assemblies are to be made at the Scientific Research Institute for Nuclear Reactors using vibration technology. This will allow further study of various problems raised by the use of MOX fuel.

At the same time it must be admitted that Russia, like other countries with well-developed nuclear power programmes, is not now able to recycle quickly all of its accumulated and accumulating reactor-grade plutonium stocks. Russia already has around 30 tonnes of such plutonium. Moreover, the RT-1 plant, reprocessing about 400 tonnes of irradiated fuel annually, produces approximately 2.5 tonnes of plutonium per year.

The situation is further complicated by the prospective substantial increase in the quantity of unused plutonium due to nuclear weapons reductions. Scientists are agreed that total plutonium recycling can only be achieved by expanding the use of fast reactors, but it looks as if this will only be possible in the next century. At present, the prospects of using light-water reactors to solve this problem are even more limited.

In Russia, work is just starting on the use of plutonium in light-water reactors. The necessary physical calculations are being performed for WWERs. Another possibility we are considering is to set up — at the plant being built in Chelyabinsk to produce fuel for fast reactors — a pilot industrial facility to produce uranium-plutonium fuel elements and assemblies for WWER-1000 reactors. In the more distant future, we plan to build a special plant in Krasnoyarsk — alongside the large-scale RT-2 spent fuel reprocessing plant currently under construction — to produce MOX fuel for WWER reactors. ❐