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Status and Prospects for Russia's Fuel Cycle

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Russia has given priority to nuclear power in its long-term strategy to increase its electricity generation capacity. But the sustainability of this strategy over the long term depends on the ability to solve problems associated with the production of increasing amounts of spent nuclear fuel. Rosatom,[1] Russia's nuclear industrial corporation, believes that development of fast neutron plutonium-breeder reactors and their fuel-cycle technologies is the solution to this problem. This article is a review of current governmental programs associated with development of nuclear power in Russia and spent fuel management.

INTRODUCTION

Russia has the world's fourth largest nuclear generating capacity, and is an important player among those countries that continue to develop new nuclear technologies. In the near term (2025–2030) light-water reactors (VVERs) are the preferred technology. In the longer term, Russia's nuclear industry believes that limited uranium supplies and increasing stocks of spent fuel require the development of a closed fuel cycle based on fast neutron plutonium-breeder reactors. To achieve this goal, Rosatom has initiated several federal target programs (FTP) aimed at the expansion of Russia's VVER capacity and the development of breeder reactors and their fuel-cycle technologies.[2] The recently adopted "Nuclear Energy Technologies of the New Generation for the Period of 2010–2015 and until 2020" (Program 2010) focuses on the development and demonstration of a variety of prototypes of fast-neutron-reactors with closed fuel cycles. But the focus on research and development suggests continued uncertainty about the path forward.

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THE STATE AND PROGNOSIS OF RUSSIA'S ENERGY PRODUCTION SECTOR

Russia is a major producer and exporter of oil and natural gas. Official data on Russia's oil reserves are classified, but published estimates rank Russia seventh in the world for proven reserves, estimated between 8 and 10 billion tons.[3] Russia's recent annual crude oil production is in the range of 0.480–0.495 billion tons. However, Russia's oil reserves are more than 50% developed, and its large fields are now going into decline. The share of secondary recovery is growing constantly and reaches up to 30–65% for the large oil companies. New oil fields are small and medium sized and much of the oil is difficult to extract. At current production levels, Russia's existing reserves will be exhausted in about 20 years.

Russia has the world's largest natural gas reserves and accounts for approximately 20% of global production. As of the beginning of 2008, Russia's reserves of commercial natural gas were 48 trillion m^3 and its resources were estimated at 164.2 trillion m^3.[4] Newly discovered deposits, however, tend to be increasingly complex and hard to tap. The challenges related to their exploitation include adverse climate conditions and locations that are remote from established centers of the gas industry and infrastructure.

Russia has significant resources of coal, estimated at more than four trillion tons. At the beginning of 2008, its reserves were ranked second in the world at 272 billion tons equating to 19% of world reserves. Russia is the fifth largest producer with 5% of world coal production. Russia's current and projected production of hydrocarbon fuels is presented in Table 1.

According to the "Energy Strategy of Russia for the period until year 2030," energy exports will be critical to Russia's economy, but their importance is expected to decline. Table 2 shows that exports of oil and coal have already plateaued and exports of natural gas are expected to plateau by 2030.[5]

The "Energy Strategy of Russia for the period until year 2030" projects that:

- A slight decline in the share of natural gas in domestic energy consumption from 52% in 2005 to approximately 47% by 2030;

Table 1: 2009 actuals and 2020 estimates of Russian production of hydrocarbon fuels (Energy Strategy of Russia for the period until year 2030).

	2009	2020
Oil (million tons)	488	476
Natural gas (billion m^3)	664	638
Coal (million tons)	326	300

Table 2: 2008 actuals and projected amounts of future exports of Russian hydrocarbon fuels to 2030.[1]

	2008	2015	2020	2030
Oil (million tons)	43	243–244	240–252	222–248
Natural gas (billion m^3)	241	270–294	332–341	349–368
Coal (million tons standard fuel)	70	72–74	74–75	69–74
Electricity (billion Kwh)	17	18–25	35	45–60

Note. [1] "Energy Strategy of Russia for the period until year 2030," Affirmed by the Order of the Government of the Russian Federation from November 13, 2009.

- Growth of the share of non-fossil fuel energy sources from 11% to 13–14%;
- A drastic (2.1–2.3 times) reduction in the improvement of energy efficiency and of the energy-production sector.

Electric Power

2011 Russian electricity generation amounted to 1040.4 billion kWh. The growth of domestic energy demand and exports projected by the "Energy Strategy of Russia for the period until year 2030" is presented in Table 3.

There are two main problems in meeting Russia's domestic demand for electricity:

- Deterioration of existing infrastructure and infrastructure in the electricity production complex; and,
- High dependence on natural gas, whose current share in the fuel supply of thermal power plants (i.e. not including hydropower) is about 70%.

For this reason, Russian energy strategy seeks a reduction of the dependence on natural gas for power production. The 2008 actuals and estimated future share of fossil fuels for thermal power plants are presented in Table 4.

The decline of the share of gas at the combustion power plants is to be compensated by an increase in the share of coal as well as by an increase of

Table 3: Russian electric power demand (Energy Strategy of Russia for the period until year 2030).

	2015 (Bln kWh)	2020 (Bln kWh)	2030 (Bln kWh)
Domestic consumption	1041–1218	1315–1518	1740–2164
Export	18–25	35	45–60
Total	1059–1243	1350–1553	1785–2224

Table 4: 2008 actuals and projections to 2030 of natural gas and coal shares for combustion electric generation in percent. The remaining fuel shares are contributed by oil, peat and wood (Energy Strategy of Russia for the period until year 2030).

	2008 (%)	2015 (%)	2020 (%)	2030 (%)
Natural gas	70.3	0–71	65–66	60–62
Coal	26	25–26	29–30	34–36

nuclear and hydropower production. Overall, by 2030, the share of non-fossil fuels for electricity production is programmed to grow from about 32% to at least 38% (Table 5).

The growth of electricity production will be accompanied by the modernization of generation infrastructure. It is planned that in 2030 natural gas in combined-cycle plants with a conversion efficiency of 53 to 55% will be the primarily method for electricity production. For coal-fired plants, priority will be given to the construction of new plants equipped with modern boiler technology with a conversion efficiency of 46 to 55%. Plans for installed electricity generation capacity in Russia up to 2030 are presented in Table 6.[6]

Russia's energy strategy gives priority to nuclear power for generation capacity. Proven and potential resources of natural uranium, accumulated reserves of purified natural and enriched uranium, reprocessed uranium and Russia's enrichment capacity provide a guaranteed fuel base for stable nuclear power development. But, along with the planned construction of current-generation VVERs, the strategy includes the development and adoption of next generation technologies. Specifically, a series of fast-neutron reactors and a closed nuclear fuel cycle that is based on the view that nuclear power can and should breed its own fissile fuel over the long term.

THE ECONOMICS OF NUCLEAR POWER IN RUSSIA

Capital Cost Increases

Nuclear power plants (NPPs) have high capital cost and relatively low operating costs. Capital costs of nuclear power have increased dramatically in

Table 5: Actual 2008 and projected share of non-fossil fuels in electric generation to 2030 (Energy Strategy of Russia to 2030).

2008 (%)	2015 (%)	2020 (%)	2030 (%)
32.5	34	35	38

Table 6: 2008 actuals and planned installed electricity generation capacity to 2030 (Energy Strategy of Russia for the period until year 2030).

Installed capacity GWe	2008	2015	2020	2030
Total	224.9	239–267	275–315	355–445
Contribution from Nuclear	23.8	28–33	37–41	52–62

the United States and Western Europe and this appears to be happening in Russia as well.

The final costs of unit No. 3 at the Kalinin NPP (2005), unit No. 2 at the Rostov NPP (2010) and unit No. 4 at the Kalinin NPP (2012), all VVER-1000s[7] whose construction was initiated in the Soviet era, were 29.7, 57.6 and 91.1 billion rubles, respectively.[8]

The estimated construction costs of the first and second units at the Novovoronezh NPP No. 2 have more than doubled. The Program 2008 allocated 111.53 billion rubles for the construction of these two units, but according to the statement of Sergey Kiriyenko, head of Rosatom, the capital costs will be about 240 billion rubles, or 3,333 USD per kW.[9] Construction delays for both units from 2012 and 2013 till 2014 and 2016 respectively could result in additional cost increases.

According to Program 2008, the construction cost of the first two VVER-1200 units at the Leningrad NPP-2, with a net installed capacity of 1.085 GWe each, is 133 billion rubles. According to current estimates by Russian experts, however, the real cost of construction of these two units will be 244 billion rubles (about 8 billion USD).[10] Construction delays will increase costs an additional 20%, which will lead to final construction costs in excess of 4,000 USD/kW.

The federal budget has allocated 50.4 billion rubles (1.65 billion USD) for the construction of the BN-800 at the Beloyarskaya NPP.[11] According to experts, however, the real capital cost of this reactor will be 160 billion rubles or 6,600 USD/kW[12] Consequently the cost of one kWe of fast reactor capacity is 1.5 times higher today than one kWe of VVER capacity.

The fact that the cost of nuclear power construction has increased significantly in Russia is recognized by the most Russian prominent nuclear experts.[13] Cost estimates reveal that nuclear power is competitive with combined-cycle natural-gas-fired units if the capital cost does not exceed USD 2,500/kWe.[14] Russia's experience with converting thermal power plants from steam-turbine cycle to combined-cycle shows that the conversion cost does not exceed 1,000 USD/kWe. Moreover, the efficiency of the converted units is increased from 35 to 55.5%, resulting in an increase in generating capacity by 60% and a reduction of gas consumption by 40% per kWh. Thus, the cost of one kilowatt of installed capacity in the new combined-cycle plant is much lower than from a nuclear power plant.

The fact that the cost of electricity generated by new nuclear power plants is much higher than combined-cycle plants shows that the 16 to 25% growth in the share of the generation contribution of nuclear power proposed in the energy strategy by 2030 is not justified economically and is motivated by other factors.

Russia's Slipping Plans for New Reactor Construction

Russia has the world's fourth largest nuclear generating capacity, 25.2 GWe in 2012, provided by 33 commercial reactors at 10 plants. Seventeen VVERs, eleven graphite-moderated, water-cooled RBMK-1000 reactors and the sodium-cooled fast-neutron BN-600 breeder prototype reactor operated with an average capacity factor of 81.2% produced 172.7 billion kWh in 2011, approximately 16.6% of the country's total electricity production.[15] Table 7 shows the growth of nuclear power in Russia between 1992 and projected to 2015.

A number of government programs that advance nuclear power have been adopted since 2006. In October 2006 the Government approved the ambitious "Federal Target Program (FTP) No. 605,"Development of Russia's Nuclear Power Industry in 2007–2010 and further to 2015" (Program 2006), that called for an increase in the nuclear share of generating capacity from 16% in 2006 to 25% in 2030.[16]

Several rationales were used to justify the adoption of this FTP. Perhaps the primary one was the replacement of hydrocarbons for domestic electricity production. This would support sustained exports of natural gas and oil, which are Russia's strategic export goods. Another motivation is the belief that the

Table 7: The actual and projected growth of nuclear power in Russia from 1992 to 2015 (Energy Strategy of Russia for the period until year 2030 and Program 2008).

	1992	2000	2005	2012	2015*
Gross Electrical Capacity, GWe	20.3	21.3	23.3	25.3	33.0
Average capacity factor (%)[2]	80	65	72.3	81.2	85
Electric energy generation (10^9 kWh)[3]	118	132	150	186	234,4
Share of total electricity generation (%)	11.8	14.8	15.8	16.6	18.6

Note. [2] B. Nigmatulin, M. Kozyrev, "Atomnaya energetika Rossii. Vremya upushchennykh vosmozhnostei (Russian nuclear power. The time of missed opportunities)," ProAtom, 6 May 2008, http://www.proatom.ru/modules.php?name=News&file=article&sid=1334.

Note. [3] Electricity production by the NPPs in Russia, http://ru.wikipedia.org/wiki/%D0%A4%D0%B0%D0%B9%D0%BB:Elektruaes.png, based on "Socio-economic indicators of Russian Federation in 1991–2010," Federal State Statistics Service, 2012.

development of nuclear energy would give rise to the modernization of Russia's industry and provide substantial support for the development of science and education in the country.

In September 2008, however, Program 2006 was replaced by the "Program of the State Atomic Energy Corporation Rosatom activity for the long term period (2009–2015)" (Program 2008).[17] Objectives of this program include:

- Ensuring the stability of the nuclear weapons complex.
- Ensuring the safe operation of nuclear facilities and the implementation of international standards for nuclear operations safety and radiation health and safety practices.

With regard to nuclear capacity growth, the 2008 Program mandates:

- Extension of the service lives of existing nuclear power plants;
- Completion of six units currently under construction (BN-800, Rostov-2 and Kalinin-4, Kursk-5, Balakovo-5 and 6); and
- Serial construction of new units on existing and new sites.

The program's first stage ran from 2009 to 2011 and the second will run from 2012 to 2015. In accordance with the program Russia's electric nuclear generation capacity will increase from 23.2 GWe in 2008 to 33 GWe in 2015. This will be achieved by completing construction and commissioning five light-water reactors with capacities of one GWe each, and one fast breeder reactor (BN-800) with a capacity of 0.8 GWe. Besides completion of the six units under construction, the program mandates the initiation of two units at Novovoronezhskaya NPP-2 and two new units at Leningradskaya NPP-2 projected to be completed between 2012 and 2013 and between 2013 and 2014 respectively. One floating plant with two KLT-40C reactors was also planned to be developed and constructed by year 2014. The program also projected that, after its implementation in 2015, Rosatom would continue by self-funding and completing no less than 2 GWe of nuclear capacity per year. In support of this strategy, the program committed a total of 1.154 trillion rubles (approximately 38 billion USD) between 2009 and 2020: 605.7 billion rubles (approximately 20.2 billion USD) from the federal budget and 548.3 billion rubles (approximately 17.8 billion USD) from Rosatom.[18] The program has slipped, however.

In 2009, Rosatom decided to temporarily halt construction of the 5th and 6th units of the Balakovo NPP due to a slowdown in electricity demand in the region and insufficient transmission capacity on existing grids.[19] Also, in early 2012, it was Rosatom abandoned completion of the 5th unit of the Kursk NPP (the last of the graphite-moderated, water-cooled Chernobyl-type RBMK-1000 reactors), which was 70% complete. This decision was motivated by new requirements for the safety of power reactors in the aftermath of the Japanese Fukushima accident.[20] Completion of the BN-800 fast-neutron reactor was postponed from 2012 to 2014.[21] Thus far, only two of the six reactors that were under construction in 2008 have been completed and are operating: unit No. 2 at the Rostov NPP (2010) and unit No. 4 at the Kalinin NPP (2012).

New construction is also lagging with respect to Program 2008. Currently BN-800, eight large VVERs and two small floating units are under construction (see Table 8).[22]

Completion of the first and second units at Novovoronezh NPP No. 2 has been postponed to 2014 and 2016 respectively.[23] As noted above, Rosatom's head, Sergey Kiriyenko has announced that the capital cost for the construction of both units has more than doubled to about 240 billion rubles, or 3,333 USD/kWe.

Construction of Leningrad NPP-2 is also behind schedule and it is suffering cost overruns. Program 2008 had the first unit coming on line in 2013, but, as of the end of 2012, it was expected to be commissioned in December 2014.[24] In July 2011, a layer of reinforcing rods in the containment of unit No. 1 peeled off during construction (Figure 1).[25] The required design changes will further increase the cost of construction.

The start-up of the third unit of Rostov NPP, which, under Program 2008 was planned for 2014, has been postponed to 2015.[26] In accordance with recent information Rosatom could reconsider the plans for construction of the Baltiyskaya NPP. Instead of two VVER-1200 units, Rosatom may consider the construction of two units powered to 680 MWe.[27]

The floating nuclear power plant was originally scheduled to be completed by 2012, but, in late 2012, Sergey Kiriyenko announced that completion would be delayed by at least one and a half to two years.[28] Financial fraud resulted in the bankruptcy of the Baltic shipyard performing the construction.[29] Recently it was announced that nuclear floating plant will be put into operation in 2016.[30]

These delays and the associated increases in construction costs indicate that Russia's nuclear industry is afflicted by many of the same problems as those in Western Europe and the United States.[31]

SPENT NUCLEAR FUEL MANAGEMENT

Spent-fuel Annual Discharges and Stocks

Russia's eleven RBMK-1000 reactors discharge about 550 tons of spent fuel annually. The spent fuel is stored in pools adjacent to the reactors and on-site in separate pools. The total original design capacity of the RBMK spent-fuel storage pools was about 6,000 tons but has been increased twice by installing higher density storage racks. Today, more than 13,000 tons of RBMK

Table 8: Nuclear power reactors under construction in Russia as of the end of 2012 (Rosatom).

				Planned grid connection	
Name	Reactor type	Site	Power MWe	(*Program 2008*)	End 2012
Beloyarskaya 4	BN-800	Beloyarsk	800	2014	2014
Baltiyskaya 1[4]	VVER-1200	Neman	1200	2016	
Baltiskyaya 2	VVER-1200		1200	2018	
Leningrad NPP2 1	VVER-1200	Sosnovy Bor	1200	2013	2014
Leningrad NPP2 2	VVER-1200		1200	2014	
Novovoronezh NPP2 1	VVER-1200	Novovoronezh	1200	2012	2014
Novovoronezh NPP2 2	VVER-1200		1200	2013	2016
Rostov 3	VVER-1000	Volgodonsk	1000	2014	2015
Rostov 4	VVER-1000		1000	2016	
Lomonosov	Two units KLT-40s	Viluyichnsk	35 x 2	2012	2015

[4]"Podgotovka ploshchadki Baltiiskoy AES vedetsya v sootvetstvii s grafikom (Construction at the Baltic NPP plant is on schedule)," Nuclear.ru, 8 December 2011, http://www.nuclear.ru/rus/press/nuclearenergy/2124099/

Figure 1: Collapsed reinforcing rods in the containment of Leningrad NPP No. 2, unit No. 1.

spent fuel is stored at Russia's nuclear power plants. Because the pools at the RBMK plants are close to capacity, dry spent fuel storage is being constructed at the Mining Chemical Combine (MCC) in Zheleznogorsk. RBMK spent fuel has lower burnup and therefore contains a lower percentage of plutonium than light-water reactor fuel. Until recently, there were no plans for reprocessing.[32]

Eleven units of VVER-1000 reactors produce 230 tons of spent fuel annually. After being stored for three to five years in the cooling ponds adjacent to the reactor sites, the spent fuel is shipped to the centralized wet storage facility at the MCC in Zheleznogorsk in Siberia near Krasnoyarsk. Cumulatively, 6170 tons of spent fuel has been discharged from VVER-1000 reactors by the beginning of 2012, and about 5000 tons of this fuel is currently stored at the MCC wet storage facility.

Six VVER-440 units discharge a total of about 87 tons of spent fuel annually. After cooling in the reactor storage pools for three to five years, the fuel is shipped for reprocessing in the RT-1 plant of the Production Association Mayak in Ozersk, near Chelyabinsk in the Urals. The VVER-440 spent-fuel assemblies are relatively small, containing only 115 kg of uranium versus 390 kg in a VVER-1000 fuel assembly.

The sodium-cooled BN-600 reactor is fueled with HEU and annually discharges 3.7 tons of spent fuel and 2.5 tons of blanket containing together 0.36 tons of plutonium. The spent fuel is cooled at the reactor site for three years before being sent to RT-1 for reprocessing.

About 140 tons of spent fuel has been discharged over the lifetimes of the four 11 MWe graphite-moderated, water-cooled EGP-6 reactors at Bilibino on Russia's Artic coast that went into operation between 1974 and 1976. All 140 tons of spent fuel is stored on-site.

Central Storage and Reprocessing

Rosatom operates three central facilities for spent-fuel management:

1. The RT-1 reprocessing plant at Ozersk has a design throughput of 400 metric tons per year. In recent decades, however, it has never reprocessed more than 100 metric tons of spent fuel of various types in a given year.[33] The plant has a spent fuel storage facility with a capacity of 2500 tons. It reprocesses the spent fuel of VVER-440, BN-600, naval and research reactors. The recovered uranium is blended to an enrichment level of 2.6% for fabrication of fuel assemblies for RBMK reactors. The high-level reprocessing waste is vitrified and placed in a storage facility. At the end of 2011, it was announced that, starting in 2013, RT-1 also will reprocess defective RBMK-1000 spent fuel assemblies.[34] About 650 tons of this spent fuel is currently stored in RBMK storage pools. The RT-1 reprocessing plant is planning to reprocess 50 tons annually.
2. A central wet spent fuel storage facility at the MCC in Zheleznogorsk has a pool with an original design capacity of 13,416 VVER-1000 fuel assemblies (6,000 metric tons). Its storage capacity has been increased to 8,600 metric tons by installing higher-density storage racks and the construction of an additional pool that was completed in November of 2011.[35]
3. The total storage capacity of a central dry-cask spent fuel storage facility of 37,785 metric tons is planned, with 26,510 tons for RBMK-1000 fuel and 11,275 tons for VVER-1000 spent fuel. A first unit of this facility, with a capacity for 1000 casks (8,129 metric tons) of RBMK-1000 fuel, was put into operation at the end of 2011, the second unit, with a capacity of 8,000 tons, is currently under construction.[36] On 5 April 2012, the first train delivered 16 tons of spent fuel from the Leningradskaya NPP.[37] Twenty-nine containers (232 tons of RBMK spent fuel) were delivered to the dry-cask storage facility from this NPP by the end of June 2013.

Direction of Nuclear Power Development and Fuel Management

Russia's community of nuclear power experts has long supported with little debate the view that the future development of nuclear power in the country should be based on the commercialization of fast breeder reactors based on a closed fuel cycle (i.e., with plutonium and uranium recycle). Rosatom, therefore, has developed a strategy focused on the development of innovative spent fuel reprocessing technologies and the development and construction of breeder reactors. This work has received support in a number of federal and departmental targeted programs.

The Federal Program, "Nuclear and Radiation Safety for year 2008 until 2015," approved by the government on 13 July 2007, proposes, among other things, the creation of infrastructure for the management of spent nuclear fuel, including construction of storage facilities, and arrangements for transportation and reprocessing. Its total budget is 145.3 billion rubles (USD 4.7 billion), including 131.2 billion rubles from federal sources. The program's priorities include:

- Reconstruction of wet and construction of new dry storage facilities for spent nuclear fuel with total capacity 38 thousand tons at the MCC in Zheleznogorsk;
- Construction of a pilot spent fuel reprocessing plant at MCC (known as Pilot Demonstration Center or ODC);
- Creation of a site for final high-level waste disposal in the Nizhnekansky granitic massif (Krasnoyarsk region).

In January 2010, Russia's government adopted another federal program, Program 2010, with a total budget 131.5 billion rubles (approximately 4.2 billion USD) of which 110.4 billion rubles (3.6 billion USD) will come from the federal budget.[38] The objective of Program 2010 is to develop prototypes of competitive and safe commercial fast and thermal neutron reactors with closed fuel cycles. Two of the goals of this program are to increase the efficiency of natural uranium in the nuclear fuel cycle by 31.8% and reduce the volume of stored spent nuclear fuel and radioactive waste per unit of nuclear power by 31% between 2009 and 2020.

In order to implement the key objectives of Program 2010, the Director General of Rosatom approved in November 2011 the departmental project, "Breakthrough," to develop new experimental fast neutron power reactors, spent nuclear fuel reprocessing technologies and technologies for production of mixed oxide (MOX) uranium-plutonium fuel.[39]

Development of New Experimental Fast Neutron Power Reactors

Currently, sodium-cooled reactors are the most developed fast-reactor technology in Russia. According to the developers of Program 2010, however, the possibility of a sodium fire, the high radioactivity of sodium induced by neutron exposure, and a local positive void reactivity effect in case of boiling do not inspire confidence in the safety of sodium fast reactors. An alternative development strategy based on lead-cooled fast-neutron reactors using a dense nitride fuel will be explored instead.

According to its promoters, the use of non-flammable and low-activating lead provides an opportunity to move to a reactor with a high level of natural convective circulation of coolant and eliminate the risk of coolant fires and explosions. They also advocate the use of high-density and high heat-conducting nitride fuel and compact electrochemical reprocessing technologies that allow co-extraction and recycle of uranium, plutonium and the minor transuranic elements.

Funding of 109.7 billion rubles (3.6 billion USD) has been committed for implementation of this research and development, including 101.3 billion rubles from the federal budget. For the design and construction of the pilot demonstrative fast-neutron lead cooled reactor BREST, the federal budget has allocated 25.7 billion rubles. NIKIET is responsible for the project and the Siberian Chemical Combine near Tomsk in Siberia has been selected as the site for the BREST reactor.[40] Reactor start is scheduled for 2020. For modeling and experimental testing of the BREST steam generator, a large liquid metal test facility ”SPRUT” has been launched at the Institute of Physics and Power Engineering (IPPE) in Obninsk outside Moscow.[41]

Lead is extremely corrosive at high temperatures, however, and some Russian experts believe that the development of the lead reactor technology will encounter great obstacles. Without creation of a reactor and materials scientific research base, it will not be possible to work out the reactor design on small test facilities. From this perspective, BREST may prove to be a risky project and could lead to an unjustified waste of financial resources.[42]

Given the risk, the developers of Program 2010 included parallel efforts to develop fast reactors with sodium and lead-bismuth coolants.

Rosatom and the private company ”Irkutskenergo” have established a joint venture for construction of a fast lead-bismuth experimental reactor SVBR-100 with a generation capacity of 100 MWe.[43] The planned cost of the project is 13.2 billion rubles, of which 9.5 billion will come from private sources. IPPE was responsible for developing the technical specifications for the reactor by the end of 2012.[44] The general designer of the reactor is VNIPIET, and EDO “Gidropress” is the constructor. The SVBR-100 will be built at the site of the Research Institute of Atomic Reactors (NIIAR) in Dimitrovgrad and is projected to be operating in 2017.

Finally, 5.366 billion rubles in Program 2010 have been allocated to the design of a larger fast-neutron sodium cooled reactor BN-1200.[45] The reactor, which is designed by the Afrikantov Experimental Design Bureau for Mechanical Engineering (OKBM), is scheduled to be completed in 2014.[46] One of the objectives of the project is to bring the cost of construction the BN-1200 comparable to a VVER of similar power. The Beloyarskaya NPP has been selected as a site for the BN-1200. If funded, construction is scheduled to be completed by 2019. The nuclear utility, Rosenergoatom has already begun an environmental impact assessment for construction and operation of this unit.[47]

Development of Advanced Spent Fuel Reprocessing Technologies

Under the Federal Program "Nuclear and Radiation Safety for year 2008 until 2015" the construction of a pilot spent fuel reprocessing facility (Pilot Demonstration Center, ODC) is ongoing at the MCC in Zheleznogorsk.[48] The center is dedicated mainly to the development of innovative aqueous radiochemical reprocessing technology for the VVER spent fuel. One of its design requirements is reduction of the high-level waste volume from reprocessing from the current level of one m^3 per ton to the level of 0.075 m^3 per ton of spent nuclear fuel. This level is expected to be achieved through the joint extraction of uranium, plutonium and minor actinides during reprocessing, and their transfer to the production of MOX fuel for burning in fast reactors.[49] The design capacity of the pilot plant was originally planned at 100 tons of spent fuel per year, and the cost of its construction was estimated at 8.4 billion rubles. Later, it was decided to increase the capacity to 250 tons per year, and the estimated cost of its construction has increased to 20.7 billion rubles (0.67 billion USD).[50] The technology to be developed and tested at the ODC will be subsequently used to design a full-scale RT-2 plant. The plan is to launch the pilot demonstration center by 2015.

Simultaneously, a multifunctional radiochemical research complex is being established at the NIIAR in Dimitrovgrad to develop spent fuel reprocessing technologies for the closed fast-reactor fuel cycle. 4.695 billion rubles has been allocated from the federal budget for its creation. As a first installation, a pyrochemical facility K-16 for reprocessing of spent MOX fuel from the BOR-60 and BN-600 reactors has been launched with a capacity of 100–150 kg of spent fuel per year.

In parallel, the Russian Federal Nuclear Center VNIITF in Snezhinsk has been chosen to develop, test, and demonstrate innovative pyro-chemical technologies for reprocessing spent nitride fuel. The reconstruction and modernization of laboratory facilities is ongoing. It is planned to use these technologies as a basis for an on-site nuclear fuel cycle, in which reprocessing and fabrication of fresh fuel would be conducted at fast reactor sites. Program 2010 includes development and experimental verification of the technology as well as design decisions related to full-scale unit during the period between 2015 and 2020.[51]

One of the claims of the advantages of the on-site nuclear fuel cycle is an increase in nuclear materials security.[52] Pyro-electrochemical methods would be used to reprocess irradiated nitride fuel in chloride salts. Plutonium would not be separated from minor transuranic elements. The presence in the

Table 9: Russian reprocessing projects

Technology	Design throughput (tons of heavy metal/year)	Location
Aqueous	250 (VVER fuel)	MCC, Zheleznogorsk
Pyroprocessing	0.1–0.15 fast-reactor fuel	NIIAR, Dimitrovgrad
Pyroprocessing	Laboratory-scale	VNIITF, Snezhinsk
Pyroprocessing	Pilot-scale	SCC, Seversk

re-fabricated fuel of minor actinides, as well as some fission products together with the absence of off-site transport of nuclear materials reduces the risk of diversion by subnational groups. Recently, it was announced that an on-site fuel cycle will be created at the Siberian Chemical Combine (SCC) site in Seversk by 2020.[53] For this purpose 2.4 billion rubles has been allocated in Program 2010 (Table 9).

Development of Technology and Production of the Mixed Uranium-Plutonium Fuel

MOX fuel for the BN-800 fast reactor will be produced from both reactor- and weapons-grade plutonium at the MCC site in Zheleznogorsk. Construction of the plant has already begun. Granulated MOX powder will be produced using the "Granat" vortex mixing technology.[54] The plant has a design capacity of 400 fuel assemblies or 12.5 tons per year and is being constructed in the same underground complex the previous location for the separation of weapon-grade plutonium from uranium irradiated in the Zheleznogorsk production reactors.[55] The projected cost of the plant is 11.7 billion rubles. Program 2010 calls for completion by 2014.[56] MOX fuel for the BN-800 will also be produced at RIAR, Dimitrovgrad, using vibro-packing technology.

In parallel, design and construction of a line for pilot production of mixed nitride fuel is proceeding. For this purpose a laboratory complex at VNIITF at Snezhinsk with a chain of hot cells with an inert atmosphere is being reconstructed and re-equipped for research and development.[57] Pilot-scale production of nitride fuel at the SCC in Seversk is already taking place, where experimental fuel elements for test irradiation in the BOR-60 and BN-600 fast neutron reactors were expected to be produced by the end of 2012.[58] The first two experimental nitride fuel assemblies, the pellets and rods for which were produced by VNIINM and assembled at the NIIAR, are already loaded for irradiation tests into the core of BN-600 reactor.[59] The Federal Program 2010 has allocated 18.164 billion rubles to develop production technologies of dense nitride fuel for fast reactors (see Table 10).[60]

Table 10: Transuranic fuel fabrication projects.

Technology	Design throughput(tons heavy metal/year)	Location
Pellet MOX for BN-800	12.5	MCC, Zheleznogorsk
Vibro-packed MOX for BN-800	1.9	RIAR, Dimitrovgrad
Nitride Fuel	For fuel tests	SCC, Seversk
Nitride Fuel	Production R&D	VNIITF, Snezhinsk

The use of LWR for Nuclear Fuel Cycle Closure

Until recently, Russia's strategy of nuclear power development has not envisaged the use of MOX fuel in VVERs. This is why, in the absence of 100% foreign funding, Russia decided not to implement the original (2000) Russia-U.S. Plutonium Management and Disposition Agreement (PMDA) to dispose of surplus weapons-grade plutonium in LWR MOX. In 2010, the parties signed a Protocol to the Agreement under which Russia would use its BN-600 and BN-800 fast-neutron reactors to dispose of 34 tons of surplus weapons-grade plutonium.

In early 2012, however, there were reports of a proposal from Rosenergoatom, the division of Rosatom that operates Russia's nuclear power plants, to use MOX fuel in the new VVER-TOI.[61] The VVER-TOI is a VVER with a capacity of 1.255 GWe whose design was scheduled for completion by the end of 2012.[62] The first VVER-TOI unit is to be built at the Nizhny Novgorod NPP site.

Rosenergoatom's new proposal is to use MOX fuel in 35% of the VVER-TOI core as well as the fast reactor BN-1200.[63] It proposed to construct VVER-TOI reactors with total capacity 27 GWe and six units of the BN-1200, as well as to create, by 2020, plants producing MOX fuel for VVER-TOI and BN-1200 with an annual capacity of 150 tons and 50 tons respectively. The plutonium that would be fed into these plants initially would be Russia's accumulated separated reactor-grade and excess weapons-grade plutonium for MOX fuel. Single BN-1200 and VVER-TOI reactors would annually require fuel containing 2.1 and 0.6 tons of plutonium respectively. If Rosenergoatom's plans are realized, the amount of plutonium irradiated annually would be 25 tons.

The realization of such a large-scale rapid expansion of Russia's MOX use seems unlikely, however. Instead, this proposal of MOX use in LWRs may be a sign of understanding among the operators of Russia's NPPs that it is unlikely that Russia's fast reactor capacity will expand rapidly enough to absorb the plutonium from large-scale reprocessing of VVER fuel.

Siting a Geological Radioactive Waste Repository

Preparations are underway for the geological disposal of high-level vitrified and long-lived radioactive wastes that resulted from reprocessing spent nuclear fuel. The creation of an underground laboratory is planned at a depth of 500 meters in the Nizhnekanskiy granitic massif at the site "Yenisei" (Krasnoyarsk region). The laboratory will investigate the geologic characteristics of the granitic massif for nine years to determine its suitability before a final decision to build the disposal facility.[64] The project was supported by local residents during the public hearing in late July 2012.[65]

CONCLUSION

Sustainable and long-term development of nuclear power depends on the ability to solve the problems associated with the disposition of increasing amounts of spent nuclear fuel. In this context, Russia's efforts to find a solution for spent fuel management are completely justified. How Russia's multiple government programs fit together is difficult to understand, however. Programs totaling trillions of rubles from the state budget were allocated without public discussion or input from the expert scientific community. The "Program of the State Atomic Energy Corporation (Rosatom) for the period 2009–2015," originally adopted in 2006 and updated in 2008, has experienced delays and cost overruns. Prospects for the Federal Program 2010 may be even worse. Its focus on the parallel development of three different fast reactor types (sodium, lead and lead-bismuth cooled) and three different fuel cycles (MOX and nitride fuel for fast-neutron reactors and MOX for VVERs) suggests great uncertainty about the prospects for success of a closed fuel cycle based on fast-neutron reactors.

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APPENDIX A: Operating Russian nuclear power plants as of August 2013

Name	Number of units	Reactor's type	Location	Gross Electrical Capacity, MW	Year of grid connection
Balakovo	1	VVER-1000	Balakovo	1000	1985
	2	VVER-1000		1000	1987
	3	VVER-1000		1000	1988
	4	VVER-1000		1000	1993
Beloyarsk	3	BN-600	Zarechnyy	600	1980
Bilibino	1	EGP-6	Bilibino	12	1974
	2	EGP-6		12	1974
	3	EGP-6		12	1975
	4	EGP-6		12	1976
Kalinin	1	VVER-1000	Udomlya	1000	1984
	2	VVER-1000		1000	1986
	3	VVER-1000		1000	2004
	4	VVER-1000		1000	2011
Kola	1	VVER-440	Polyarnyye Zori	440	1973
	2	VVER-440		440	1974
	3	VVER-440		440	1981
	4	VVER-440		440	1984
Kursk	1	RBMK-1000	Kurchatov	1000	1976
	2	RBMK-1000		1000	1979
	3	RBMK-1000		1000	1983
	4	RBMK-1000		1000	1985
Leningrad	1	RBMK-1000	Sosnovy Bor	1000	1973
	2	RBMK-1000		1000	1975
	3	RBMK-1000		1000	1979
	4	RBMK-1000		1000	1981
Smolensk	1	RBMK-1000	Desnogorsk	1000	1982
	2	RBMK-1000		1000	1985
	3	RBMK-1000		1000	1990
Novovoronezh	3	VVER-440	Novovoronezh	417	1971
	4	VVER-440		417	1972
	5	VVER-1000		1000	1980
Rostov	1	VVER-1000	Volgodonsk	1000	2001
	2	VVER-1000		1000	2010