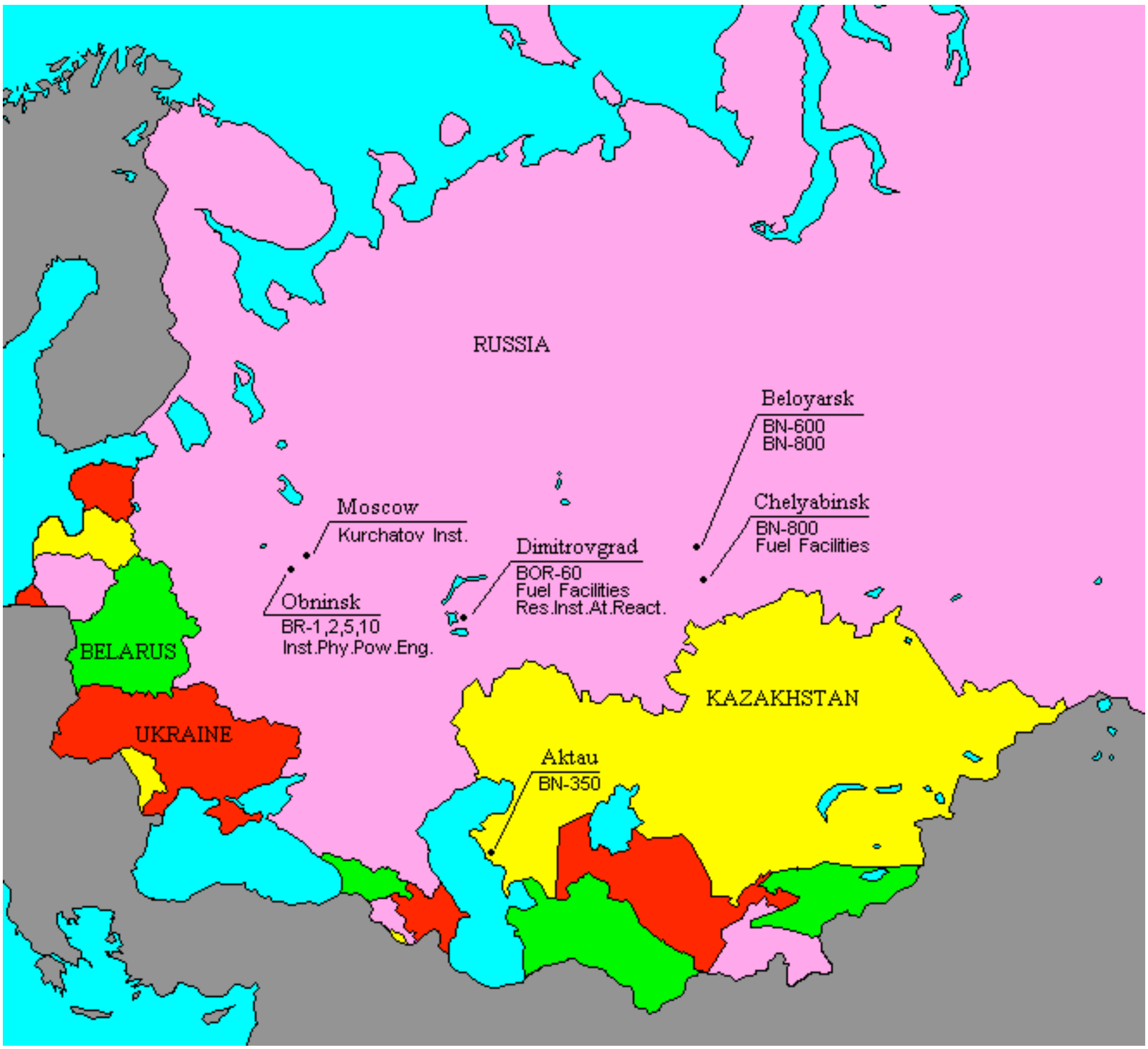
Overview of Fast Reactors in Russia and the Former Soviet Union

The Soviet fast reactor development program proceeded in a step-wise manner toward development of commercial-sized plants. Small fast reactor facilities (BR-1, BR-2, and BR-5) were constructed in the 1950s and 1960s, and operational results were utilized to refine the design and construction of larger plants. The large power plant facilities currently developed in this program are BOR-60, BN-350, BN-600, and BN-800. The locations of the fast reactor plants and related facilities are shown below.



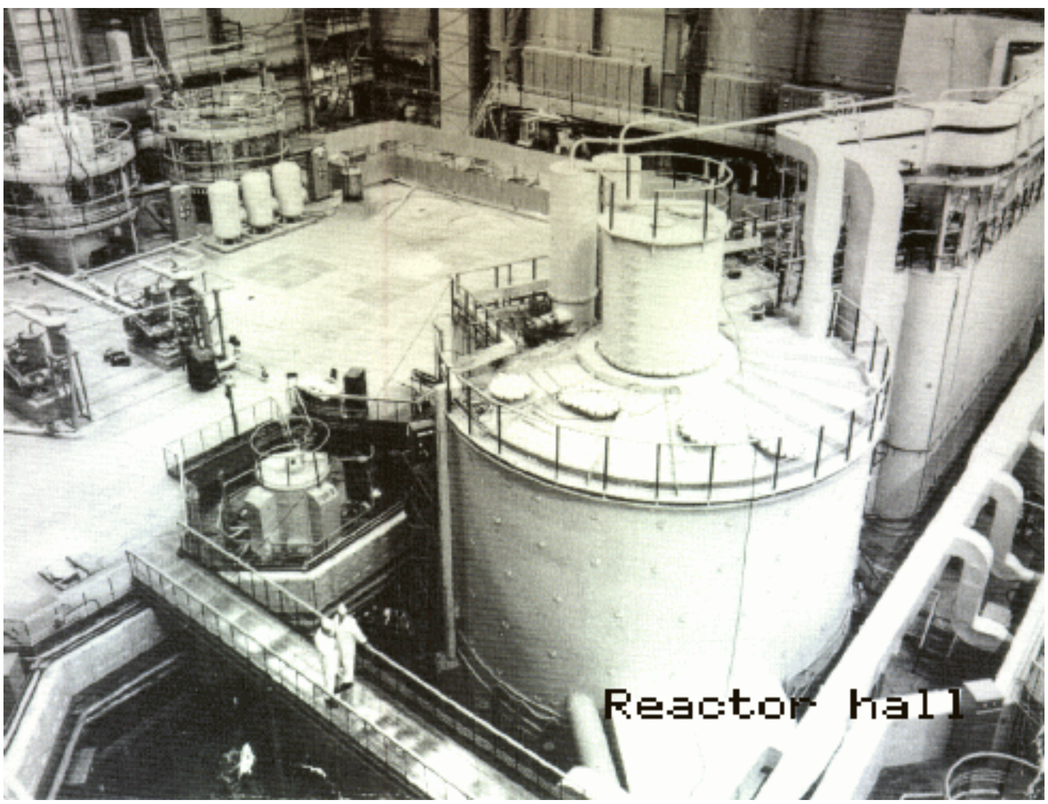
It should be noted that with the breakup of the former Soviet Union, all fast reactor related facilities became the property of the Russian Federation with the exception of BN-350 which is located in Kazakhstan.

Fast reactor work in Russia and the former Soviet Union dates from the early 1950s, when the BR-1 and BR-2 projects at Obninsk were initiated. BR-1 was a zero power critical assembly, fueled with plutonium metal, with a core volume of 1.7 liters. The reactor was upgraded in 1956, was renamed BR-2, and was operated at a thermal power level of 100 kW. Mercury was used as the coolant.

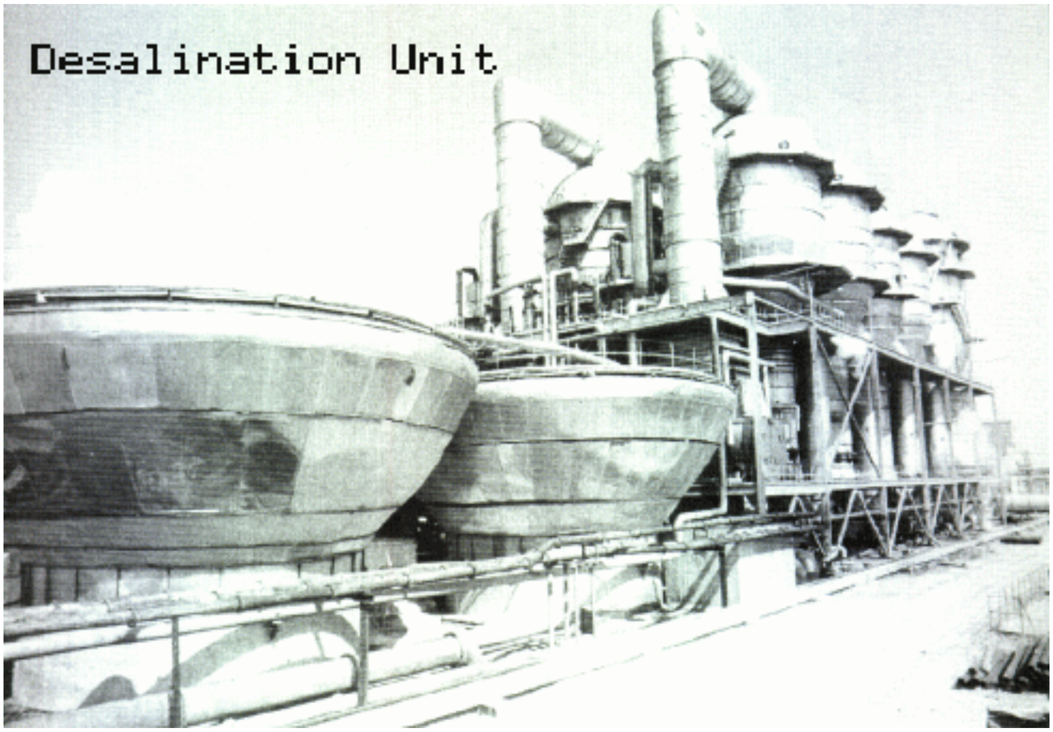
BR-2 was soon replaced by BR-5, which attained criticality in 1958 and was operated at 5 MW(thermal). This project was developed primarily to gain experience in operating a multi-loop, sodium-cooled reactor and to test fuel elements and equipment for subsequent fast reactors. BR-5 was the first reactor in the world to be operated with plutonium oxide fuel. Although several fuel elements developed leaks, the reactor was successfully operated until November 1964, when it was shut down and reloaded with a uranium carbide core. In 1972, the reactor was modified again, this time for 10 MW(thermal) operation with a new PuO2 core. This upgraded facility has since been known as BR-10.

The BOR-60 program was carried out at the Research Institute of Atomic Reactors (RIAR), Dimitrovgrad; this work focused on the development and irradiation of fuel and structural materials for sodium-cooled fast reactor systems. Construction of the 60 MW(thermal) BOR-60 reactor was started in 1964, and criticality was attained in 1968. Since it was built primarily to provide a materials test bed, the heat was originally rejected by air-dump heat exchangers. A steam generator was installed in 1970 and a second steam generator of a different design was put into service in 1973. The reactor could then generate electricity at the rate of 12 MW.

The BN-350 sodium-cooled fast reactor, shown below, situated near the city of Aktau (formerly Shevchenko) in Kazakhstan has been in operation since 1972.



BN-350 was designed for the dual purpose of producing electricity (150 MW) and desalting water (120,000 m³ fresh water/day), which corresponds to a total power generation of 350 MW(electric).



The system was built to prove that a commercial-size fast reactor could be constructed using the manufacturing methods and materials developed and tested in the BOR-60 program. Experience has shown that the operation and maintenance costs (reliability, availability, capacity factor) of power generation for the BN-350 plant are economically competitive with traditional (fossil-fuel or light water reactor) power plants; however, the capital cost was high for this demonstration plant. The BN-350 reactor system has also been utilized for a wide range of experimental work supporting fast reactor development; and several design improvements were developed for the next generation, BN-600, design. However, in June 1994, the reactor was shut down because of a lack of funds to buy fuel. In addition, the operating license of BN-350 has now expired. It is reported that Russia's Ministry of Atomic Energy (MINATOM) has proposed a joint project to the Kazakh Atomic Energy Agency for extending operation of the BN-350 by up to 10 years, then decommissioning it and providing replacement power. According to another report, the Kazakh State Corporation for Atomic Energy plans to build a second 135 MW(electric) fast reactor to replace the BN-350.

The BN-600 sodium-cooled fast reactor built at the Beloyarsk Nuclear Power Station, designed for 600 MW(electric), produces 560 MW(electric) and has been in operation since 1980. Significant improvements (over BN-350) were applied in the secondary system and the fuel discharge burnup was doubled. These measures significantly decreased the capital investment; however, the BN-600 electrical generation cost is still twice that of a VVER-1000 reactor. Experimental studies were performed in BN-600 to evaluate the safety performance of fast reactor power plants, and to investigate a variety of advanced materials; several design improvements were developed for the next generation, BN-800, design.

The developmental and design work for the BN-800 design was completed and construction started at two sites, Beloyarsk and South Urals in 1986. Construction was suspended between 1990-93 because of economic crises and negative public opinion in the wake of the Chernobyl accident, although the current Russian energy program calls for completion of the first unit in 2000. The BN-800 design incorporates improvements in the secondary system and reactor materials as developed in the BN-600 testing program. Recent changes in the Russian nuclear regulations (zero-void-worth criterion) and increased collaboration with the Western countries have led to recent studies of modified BN-800 core design configurations. In the original conception of the Russian fast reactor program, the BN-800 was viewed as a scaling step toward the development of a large-scale BN-1600 reactor for commercial application, planned for Obninsk; however, the current status of this project is uncertain given the delayed BN-800 construction schedule.

Overall, the Russian sodium-cooled fast reactor systems are similar to designs developed and utilized elsewhere. The BN reactors currently utilize enriched UO_2 fuel, but the BN reactors were originally designed to use UO_2/PuO_2 mixed oxide (MOX) fuel with operating conditions roughly similar to the French or U.S. designs.

In addition to the BN program, Russia has been proceeding with fast reactor design R&D. The Ministry of Atomic Energy has announced the completion of design work on the BNM-170, a new modular fast reactor, similar in concept to the ALMR designs that were being developed in the U.S. The Institute of Physics and Power Engineering at Obninsk is investigating the possibility of reducing the positive sodium-void effect for the BN-800 by changing the core design. The Kurchatov Institute and the Research and Design Institute for Power Engineering (RDIPE) in Moscow are actively designing a passively-safe lead-cooled fast reactor.

Design Characteristics

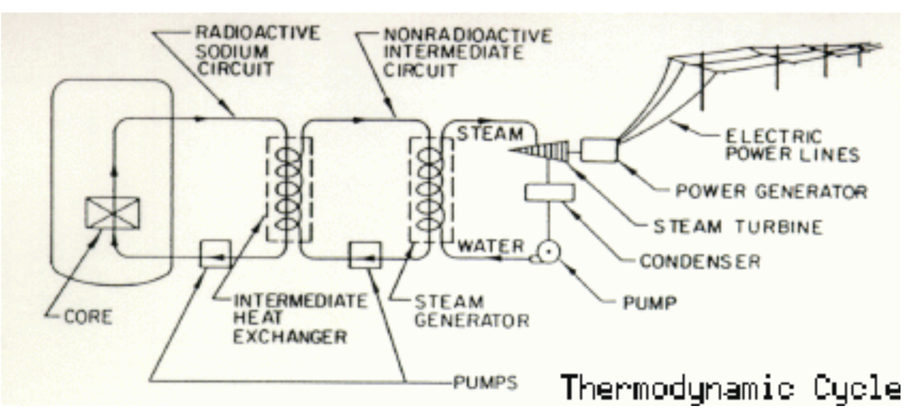
In Table I, the core design characteristics of the existing Russian fast power reactors are summarized. All of the fast power reactors were designed to be able to operate on MOX fuel, and MOX fuel experiments have been conducted in BOR-60, BN-350, and BN-600. However, only the BOR-60 reactor has ever operated with substantial MOX fuel loadings. The demonstration reactors, BN-350 and BN-600, were originally designed to utilize enriched UO2 only for their initial core loadings, but these designs have continued to operate on enriched uranium fuel (approximately 20% U235).

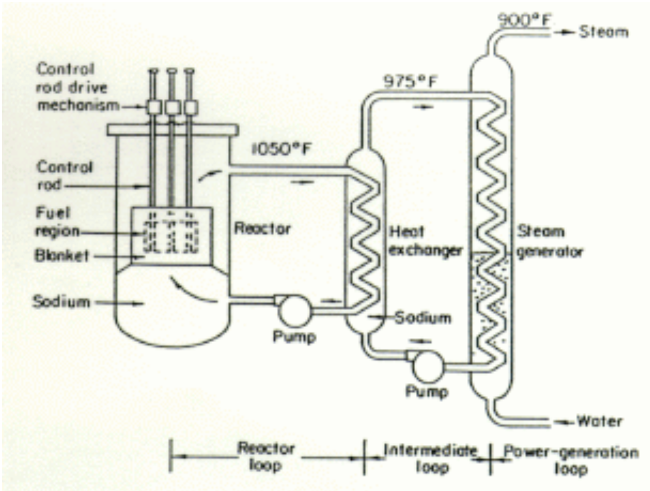
Table I Summary of Design Characteristics

Reactor	BOR-60	BN-350	BN-600	BN-800
Power, MW(electric)	12	350[1]	600	800
Operating Dates				
Start of Construction	1964	1964	1967	1986
First Criticality	1968	1972	1980	2000
First Electricity Generation	1969	1973	1980	N/A
Fuel Description Type	MOX	UO2	UO2	MOX
Enrichment (% fissile/heavy metal)	45-75	17/26	17/21/26	20-30
Plant Configuration	loop	loop	pool	pool
Active Core Physical Dimensions, m				
Diameter	0.46	1.52	2.06	2.47
Height	0.46	1.07	0.76	0.95

[1]including the equivalent of 200 MW (electric) for desalting water

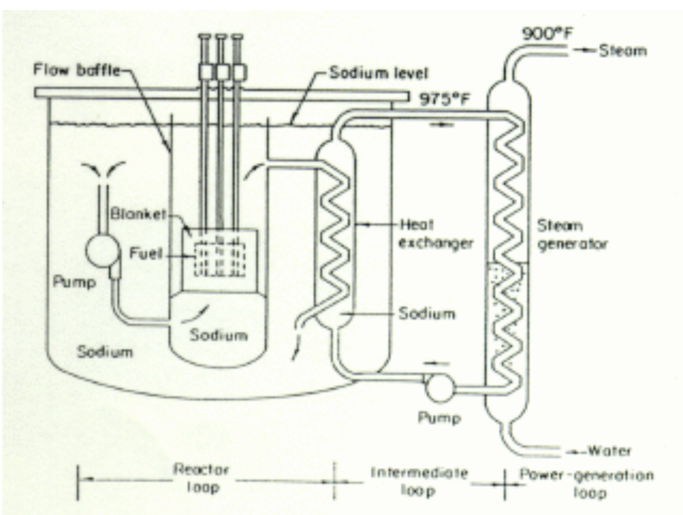
The BN-350 reactor plant is a "loop" design, where the reactor is located in a separate vessel, and piping connects the reactor vessel with all other major system components, such as coolant pumps, and the intermediate heat exchangers.





There are six loops in the BN-350, five of which are on-line in normal operation and one in a backup mode. Secondary sodium loops connect each intermediate heat exchanger with the steam generators. Steam is used in three steam turbines to generate electricity and in a sea water desalination facility. The principal engineered safety feature is the use of guard vessels around the reactor vessel and loop piping. The entire reactor plant is housed in a concrete rectilinear building, which is not considered a "containment" in the usual sense, but is more of a standard industrial building. However, there is a building exhaust filtration system capable of removing radioactive gas released from the reactor vessel, as well as a gas containment hood above the reactor vessel cover. There was one safety-related incident, in 1975, involving a sodium/water reaction from a steam generator leak, which led to a sodium fire which lasted for two hours, but did not prevent restarting of the facility.

The BN-600 reactor plant is of a different design, using a "pool" concept where the reactor, coolant pumps, and intermediate heat exchangers are all located in a common sodium pool, as shown below.



The piping connecting these major components is also contained in the sodium pool. Component size has been increased from BN-350, not only to handle the greater power, but also in response to a design change, where the number of coolant loops has been reduced from six in BN-350 to three in BN-600, mainly in an effort to reduce the capital cost. All three loops in BN-600 are functioning in normal operation, although the steam generator is modular in design, allowing it to be repaired while the plant is online. The power generation system in BN-600 is more conventional than for BN-350, with steam used only to generate electricity. In addition to the guard vessels around the reactor vessel and piping, as in BN-350, the use of a pool-type design where there are no penetrations in the reactor vessel which could lower the sodium level is also considered an engineered safety feature. The reactor system is housed in a concrete rectilinear building, as with the BN-350, and is provided with the same filtration and gas containment features. There have been incidents involving sodium/water interactions from tube breaks in the steam generators, a sodium fire from a leak in an auxiliary system, and a sodium fire from a leak in a secondary coolant loop while shut down. All of the incidents were classified as the lowest level on the International Nuclear Event Scale, and none of the events prevented restarting operation of the facility after repairs.

The BN-800 design is similar to the BN-600, with most of the plant layout and major dimensions being identical. One significant difference is that the three heat transport loops drive a single steam turbine in BN-800. The reactor plant was originally planned to be housed in a concrete rectilinear building as with BN-350 and BN-600, not a containment, but the design is still in review in light of a more stringent safety environment.

Fuel Fabrication and Performance

As described above, the existing power plants (BN-350 and BN-600) primarily operate with an enriched uranium oxide fuel cycle. The manufacture of fuel elements is fully automated. Quality control assessment of the welding, fuel rod integrity, density, geometrical parameters, etc. is automatically checked by ultrasonic methods. The technology used for fuel fabrication has practically eliminated fuel element failures.

Although commercial scale fabrication of MOX fuel has not been demonstrated, several research facilities at Chelyabinsk have developed MOX fuel fabrication technology. Two small facilities ("Pilot Bay" and "Zhemchug") have been closed, two ("Granat" and "Pakat") are currently operating, and one, "Complex 300" (Tsech 300), has been under construction since 1984. The Complex 300 plant was designated to manufacture fuel subassemblies for the BN-800 reactors of the South Urals project at Chelyabinsk. At this time, financial problems have stalled continuation of both the BN-800 reactor and Complex 300.

Considerable mixed oxide (MOX) irradiation data have been obtained, as listed in Table II. The BOR-60 reactor began operation with MOX fuel in 1981, and test subassemblies were inserted into BN-350 in 1985 and into BN-600 in 1988. MOX fuel has been successfully irradiated to the very high burn-up of 24% in the BOR-60 reactor and to 9.6% burn-up in BN-600.

Table II Fast Reactor Tests of Pu-Containing Fuel

Reactor	Time of Testing	Testing Scale
BOR-60	From 1973	Tens kg Pu
	From mid-1980s	Up to 10 kg Pu
BN-350	From 1980	10 fuel assemblies
	1990-1992	100 fuel elements
BN-600	From 1990	8 fuel assemblies

Reprocessing

Spent fuel from BN-350 and BN-600 is reprocessed at the Radiochemical Plant (RT-1) at Chelyabinsk-65. RT-1 is a chemical separation plant using the PUREX process that began operations in 1956 by processing spent fuel from military production reactors. It was modified to handle stainless steel and zircaloy clad spent fuel. In 1976, operations were shifted from processing military production reactor fuel to processing spent fuel from naval reactors (submarine and civilian icebreaker), test reactors, the first generation light-water reactors (VVER-440s), and the two demonstration fast reactors (BN-350 and BN-600). It is the only facility for power and naval reactor fuel reprocessing in Russia.

The RT-1 reprocessing plant capacity is 400 metric tonnes per year (MT/y) of heavy metals, which is comparable to the capacity of the UP2 plant that was operated by Cogema at La Hague in France from 1966-1990. In 1989, it was reported that the throughput for RT-1 had averaged 200 MT/y over the previous 10 years. The rate of spent fuel reprocessing has declined recently, with 160 MT/y processed in 1991, 120 MT/y in 1992, and less in 1993, largely due to transportation problems and a law restricting the import of nuclear waste into Russia.

The RT-1 facility currently provides 99% recovery of uranium and plutonium and 85% recovery of neptunium from spent fuel. At a reprocessing rate of 120 MT/y, 114 MT/y of low enriched uranium (1.25% U235) and 1 MT/y of reactor grade plutonium are recovered. Originally the plutonium was intended for use in fast reactors in the form of MOX fuel. However, due to delays in the fast reactor program and in the construction of the Complex 300 fuel fabrication plant, PuO2 is currently placed into temporary storage at Chelyabinsk-65. The majority of the neptunium dioxide is also sent to storage, with the remainder being used for production and research activities. The recovered uranium is blended with enriched uranium feedstock to produce the desired RBMK fuel enrichment (2.4% U235).

The Research Institute of Atomic Reactors (RIAR) facility at Dimitrovgrad has demonstrated 99.8% fuel utilization through small scale closure of the fuel cycle, by producing fuel from recycled BN-350 reactor fuel for testing in the BOR-60. RIAR has also investigated closed-cycle pyrochemical processes for fast reactor fuels. Since the 1970s, the effort has been directed to oxide fuels. The program has been supported with considerable basic chemical studies. Both pyroelectrochemical and fluoride volatility processes have been investigated. Although the latter may have promise for thorium-uranium fuel, the former is preferred for uranium-plutonium fuel. Irradiated UO2 fuel has been processed on a laboratory scale by fluoride volatility. Investigations of pyrochemical processes for fast reactor fuel has resulted in enough information to proceed with the design of a production-scale plant.

Russian Plans for Future Deployment

Russian (MINATOM) policy regarding fast reactor deployment has been stated in several recent papers authored by Minister Mikhailov and collaborators. Quoting directly:

1. *The Russian concept of plutonium management (both civil and weapons) is based on the postulate of the outer fuel cycle closure, necessity to enhance fuel efficiency, and decreasing radioactivity of disposed long-lived wastes.* [Note: outer fuel cycle closure refers to the overall nuclear power regime continuing both thermal and fast reactors, reprocessing plants, and MOX fuel fabrication facilities]

2. *In view of plutonium utilization of existing fast reactors being restricted, safe and reliable storage of separated civil plutonium at PO Mayak and ex-weapons plutonium is required.*

3. *Longer range plutonium disposition options are based on development of a Nuclear Power Center at PO Mayak (RT-1, Complex-300 and 3 BN-800s) to use accumulated civil and ex-weapons plutonium in fast reactors.*

4. *Long-term management options, which call for fulfillment of research, envisage burning of excess plutonium and minor actinides in fast reactors with new core compositions.*

5. *Investigation is underway to estimate plutonium utilization options, possibly using foreign technology including those on light-water reactors and CANDU in the framework of defense nuclear centers concept.* [Note: refers to the Tomsk and Krasnoyarsk defense reactor replacement power]

6. *International cooperation with the aim not only to develop the current technical policy but also to determine the optimum long-term disposition is required.*

and:

The economic difficulties that delayed the realization of the programme of the construction of NPPs with commercial reactors BN-800, the U-Pu fuel manufacturing complex at PO "Mayak", a new reprocessing plant RT-2 in the Krasnoyarsk region have in no way changed the general direction of Pu recycling to power engineering. Today our first rate target is to construct a semi-commercial low capacity (up to 50 fuel assemblies/annum) facility for U-Pu in place of the obsolete one "Granat" at the PO "Mayak" and to update the "Paket" facility for manufacturing pellets and fuel rod stacking. These production facilities have to provide fuel for the BN-600 reactor with the hybrid core when the U load is to be gradually replaced by the U- Pu one. Assistance and help of foreign investors could significantly accelerate the introduction of the "small" recycle of Pu to fast reactor base power engineering.

The rationales which underlie the Russian policy have been developed based on engineering and economics studies.

These rationales are discussed in the papers by Minister Mikhailov; in summary,

1. Use of Russian inventories of plutonium for domestic electricity production in fast reactors facilitates (frees up) their inventories of enriched uranium for commercial export to generate hard currency,

2. In Russia, the technology for MOX fueling of fast reactors is more advanced than is MOX fueling of thermal reactors,

3. Cost studies have shown that the new thermal reactor designs which meet revised safety requirements are more expensive than previous Soviet VVER designs and in fact are on a parity with the BN-800 design -- which also meets the revised safety standards, and

4. MOX utilization in thermal reactors actually exacerbates the nuclear waste disposal issues (more long-lived radiotoxicity is generated), whereas MOX utilization in fast reactors mitigates these issues.

See also the presentation that accompanies this text.

Source: ***ANL Report***

List of other BN-800 related documents
