ON CONVERSION OF RESEARCH REACTORS IN RUSSIA

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The nuclear research facilities (NRF) – research reactor (RR), critical (CA) and subcritical assemblies (SCA) – played a crucial role in obtaining basic and applied knowledge in the field of nuclear physics. As a source of neutrons, the NRF represent a unique tool for experimental research in various fields of science and technology. Creation of nuclear weapons and nuclear energy development would be impossible without them. The number of the NRF in the world increased rapidly especially in 50-70s of the last century and by the mid '70s has reached the maximum of 390 NRF.[2] Over time, NRF began to be used not only to solve the problems of defense, basic research and nuclear energy, but also in other sectors, including medicine and biology. Dozens of NRF were delivered by the Soviet Union and the United States to other countries. According to IAEA, 692 NRF of different types and different capacities were built in the world over whole period of the development of nuclear physics.[3]

But by the early 80's the growth of number of nuclear research facilities in the world has stopped. By this time, the powerful RRs have achieved significant neutron flux density (0.5×10^{15} n/cm^2 × sec), and attempts to further increase this parameter faced the problem of insufficient stability of RR construction materials. The solution of material science problems required significant research and funding efforts. On the other hand, by this time a significant base of experimental data have been accumulated, the use of which allowed to develop and verify computer programs to solve many practical problems in various fields without the use of NRF. For these reasons, since the mid-80s, the construction of new NRF has virtually stopped, and the process of their decommissioning became predominant. At present, there are 232 active NRFs in the world, and only 7 under construction or planned for construction.[4]

The principal characteristic of RR is the ratio of the neutron flux density to the reactor power. From the very beginning of the NRF development the top priority for researchers and designers was obtaining a greatest magnitude of neutron flux density into experimental channels while minimizing power reactor. Achieving the maximum value of this parameter requires minimization of the RR core and the use of uranium fuel with the highest possible enrichment. For this reason, the majority of the RRs in Russia and in the United States were constructed with the use of HEU fuel, the enrichment of which reached 90% of U235.

In the late 70's, both the U.S. and the Soviet Union recognized the importance of the research reactors conversion from HEU to LEU fuel, because these reactors were the main consumers of HEU for civilian purposes, and supply of HEU fuel for the RRs in

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[2] Aksenov V.L., Archangel'sky N.V., Lopatkin A.V., Tret'yakov I.T. "Research reactors: crisis or milestones' change?", report at the International Scientific and Technical Conference "Research Reactors in XXI Century", June 20-23, 2006, Moscow.

[3] IAEA Research Reactors Database, http://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx?filter=0

[4] "Research Reactors: Purpose and Future", IAEA Report, http://www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/documents/RR_Purpose_and_Future_BODY.pdf

other countries creates a definite risk to non-proliferation regime.[5] For this reason, the two countries initiated programs to develop and produce fuel for the RRs supplied to other countries, in which the enrichment of uranium was decreased from 80-90% to 20-36%. The Soviet program on reducing enrichment of fuel for research reactors was adopted in the early '80s.[6] The program included two stages of implementation: the first stage to reduce the enrichment down to 36%, and the second – below 20%.

In 1993, Russia and the United States began collaboration on the development of low-enriched fuel for RRs supplied by Russia (USSR) to other countries. This cooperation, carried out under the program *Reduced Enrichment in Research and Test Reactors* (RERTR) is currently ongoing. In 1994, the Ministry of Atomic Energy of the Russian Federation initiated the program "Creation of fuel rods and fuel assemblies with 20% uranium-235 enrichment fuel for the cores of research reactors."[7] The main goal of the program is the development and organization of the production of fuel assemblies for Soviet design reactors in third countries. The program consists of three main stages:

1. Design and creation of fuel rods and fuel assemblies with fuel based on UO2-Al.
2. Design and creation of fuel rods and fuel assemblies with high-density fuel based on uranium-molybdenum alloys.
3. The development of fuel rods and fuel assemblies for the new generation of research reactors.

This program involves JSC TVEL, NIKIET, VNIINM, JSC NCCP, NIIAR, IPPE, IRM, RRC KI, and St. Petersburg Institute of Nuclear Physics of the Russian Academy of Sciences. As a result of the laboratory, design and technological development, and post-irradiation examination the work on the first phase is completed. The production of fuel assemblies (FA) VVR-M2 and FA of IRT-4M with enrichment below 20% is organized at the Novosibirsk Chemical Concentrate Plant for the RRs of Hungary, Ukraine, Vietnam, the Czech Republic, Uzbekistan, Libya, Bulgaria, North Korea.

Implementation of the first stage laid the foundation for the successful implementation of the intergovernmental U.S.-Russian agreement on "Cooperation for import to Russia of nuclear fuel from research reactors, produced in the Russian Federation" (RRRFR program). With the conclusion of this agreement in May 2004, the program of the research reactors conversion and removing Russian-made fresh and spent HEU fuel from third countries to Russia received an additional boost. The program involves 14 countries: Belarus, Bulgaria, Hungary, Vietnam, Kazakhstan, Latvia, Libya, Poland, Romania, Serbia, Ukraine, Uzbekistan, Czech Republic. As the result of RRRFR program implementation some 1930 kg of fresh and spent HEU fuel was returned to Russian Federation by the end of 2012.[8] The entire stockpiles of HEU fuel

[5] Highly enriched uranium is the uranium with U235 isotope concentration higher than 20%.

[6] N.V. Arhangelskiy, "Problems of Research Reactors Conversion from HEU to LEU. History and Perspective", Russian-American Symposium on the Conversion of Research Reactors to LEU Moscow, 8 June, 2011.

[7] Aden V.G., Kartashev E.F., Lukichev V.A., Lavrenyuk P.I., Troyanov V.M., Enin A.A., Tkachev A.A.,Vatulin A.V., Dobrikova I.V., Suprun V.B. "Russian Program of the Decreasing of Fuel Enrichment in Research Reactors: Status and Perspectives", International Scientific and Technical Conference "Research Reactors in XXI century", June 20-23, 2006, Moscow.

[8] A. Smirnov, and at all, "Ten Years of RRRFR Program", Safety of Nuclear Technologies and Environment", №1, 2013

were removed from Latvia, Bulgaria, Romania, Libya, Serbia, Ukraine and Vietnam.[9] It is important to note that the U.S.-Russian cooperation on the RR conversion and return of fresh and spent HEU fuel was supported by the joint statement of the Russian and U.S. presidents Vladimir Putin and George W. Bush in 2005, and Dmitry Medvedev and Barack Obama in 2009.

In Russia, despite the fact that the country has the largest number of HEU fueled RRs, the task of converting its own reactors to minimize the use of HEU was not considered until recently. Discussion of this topic among Russian experts has started only in connection with the Agreement between Rosatom and the U.S. Department of Energy, concluded in December 2010, to conduct a preliminary study on the possibility of converting six Russian RRs.[10]

Based on available information about the current status of the RR and plans for their use in Russia, this paper is devoted to the assessment of the prospects for their conversion.

[9] HEU Flies Back to Russia, World Nuclear News, 04 July 2013

[10] "Six Russian reactors will be converted to low enrichment fuel", Nuclear.Ru, 07.12.2010, http://www.nuclear.ru/rus/press/other_news/2118672/

The fleet of the Russia's Research Reactors

The possibility and necessity of conversion of each individual reactor is mainly determined by its purpose, features of the core design, as well as plans for its future use. At the end of 2011 there were 32 civilian RR in Russia (see Table 1). This number does not include reactors that belong to VNIIEF and VNIITF since they are used in the defense programs.

Table 1. List of Russian Civil Research Reactors

No.	Name	Owner	Power, MW	Commissioning/ Reconstruction	License No./Expiration Date	Type of license
1	IRT*	Moscow Institute of Engineering and physics (MEPhI)	2.5	1967 / 1975	GN-03-108-1557 Until 30.06.2009	Operation
2	VVR-Ts	Karpov Scientific Research Institute of Physical Chemistry in Obninsk	15	1964 Currently modernization work is carrying out	GN-03-108-2185 Until 22.09.2014	Operation
3	IR-50	Scientific Research and Design Institute of Power Engineering (NIKIET)	0.05	1961	GN-03-108-2214 Until 26.11.2014	Operation
4	TVR	Institute of Theoretical and Experimental Physics (ITEPh)	2.5	1949	GN-04-108-1786 Until 31.12.2012	Decommissioning
5	BR-10	Institute of Physics and Power Engineering (IPPE)	8	1959	GN-03-108-1609 Until 31.12.2011	Operation in final closedown mode
6	AM-1	IPPE	10	1954	GN-04-108-2349 Until 21.04.2017	Decommissioning
7	Bars-6	IPPE	6.5 MJ, impulse	1994	GN-03-108-2515 Until 31.05.2016	Operation, and decommissioning
8	IBR-2 (IBR-2M)	Joint Institute for Nuclear Research (JINR)	2, impulse	1984 / 2011	GN-03-108-1611 Until 31.12.2011	Operation
9	IBR-30	Joint Institute for Nuclear Research (JINR)	0.025, impulse	1969	GN-04-108-1228 Until 31.01.2007	Excluded from the list of RRs, CTSs and SCTSs.
10	F-1	Russian Scientific Center "Kurchatov Institute" (KI)	0.024	1946	GN-03-108-1801 Until 31.01.2012	Operation
11	Argus*	KI	0.05	1981	GN-03-108-2159 Until 17.07.2014	Operation
12	IR-8*	KI	8	1957 In 2001 service life was extended until 2005	GN-03-108-1608 Until 31.12.2011	Operation
13	MR	KI	50	1964	GN-04-108-2490 Until 04.02.2016	Decommissioning of nuclear facility
14	GIDRA	KI	Impulse	1972 / 2003	GN-03-108-2000 Until 31.01.2014	Operation
15	Gamma	RNTs KI	0.125	1982	GN-03-108-1646 Until 30.03.2012	Operation
16	OR*	RNTs KI	0.3	1954 / 1988	GN-03-108-1859 Until 30.06.2013	Operation
17	Bars-4	Scientific Research Institute for Instruments (NIIP)	4 MJ, impulse	1971	GN-03-108-1619 Until 31.12.2011	Operation

18	VVR-M	Petersburg Nuclear Physics Institute in Gatchina	15	1959	GN-03-108-1699 Until 30.07.2012	Operation
19	SM-3	Scientific Research Institute of Atomic Reactors (NIIAR)	100	1992	GN-03-108-1980 Until 31.12.2011	Operation
20	RBT-6	NIIAR	6	1975	GN-03-108-1950 Until 31.10.2011	Operation
21	RBT-10/1	NIIAR	10	1983	GN-03-108-1956 Until 31.12.2013	Decommissioning
22	RBT-10/2	NIIAR	10	1984	GN-03-108-2530 Until 30.06.2016	Operation
23	MIR-M1*	NIIAR	100	1966 / 1975. Modernization project is developed	GN-03-108-2234 Until 31.12.2014	Operation
24	Arbus (ACT-1)	NIIAR	12	1963	GN-04-108-2161 Until 17.07.2014	Decommissioning
25	VK-50	NIIAR	220	1965 Service life of reactor vessel was extended up to 2015, SUZ – up to 2007	GN-03-108-2467 Until 25.12.2015	Operation
26	BOR-60	NIIAR	60	1969 Work is carrying out on life extension	GN-03-108-2233 Until 31.12.2014	Operation
27	IVV-2M	Institute of Reactor Materials (IRM)	15	1966 / 1982	GN-03-108-2438 Until 21.10.2015	Operation
28	U-3	The Krylov Central Research Institute	0.05	1964 / 1989	GN-03-108-2465 Until 24.12.2017	Operation
29	IRT-T*	Scientific Research Institute of Nuclear Physics at the Tomsk Polytechnic Institute	6	1967 / 1984	GN-03-108-2452 Until 11.11.2015	Operation
30	VVRL-02 VVRL-03	Scientific research institute of instruments (NIIP)			GN-04-108-1587 From 31.10.2006 Up to 31.10.2011 License was withdrawn by decision No. 1587/A from 31.03.2011	Excluded from the list of RRs
31	PIK	Petersburg Nuclear Physics Institute in Gatchina	100	2011	GN-03-108-2385 Until 21.06.2015	Operation
32	IRV-M1/ IRV-M2	NIIP	4	1974-1999	GN-02-108-2489 Until 04.02.2016	Construction

* – reactors for which the preliminary study of the possibility of conversion is carried out according to the agreement between Rosatom and U.S. Department of Energy.

According to the Federal Service for Ecological, Technological and Nuclear Supervision data for 2011, only 22 RRs out of 33 have license to operate. Three RRs (IBR-30, VVRL-02, VVRL-03) are completely stopped and considered as excluded from the list, and eight RRs have a license for decommission or work in the final shutdown mode (MR, Gamma, RBT-10-1, Arbus, BR-10, AM-1, BARS-6 TVR). Only eighteen RRs out of 22 that have a license for operation are of interest for this paper because they use HEU fuel. Brief information on these reactors is presented below.

BOR-60 *(NIIAR)*

Large experimental fast reactor with sodium coolant and 60 MW thermal power BOR-60 is designed to test fuel elements based on different fuel compositions containing plutonium. It is also used for engineering and technological studies to substantiate projects on the development of fast neutron reactors with sodium coolant, including safety studies. In addition this reactor is used for irradiation of structural materials for nuclear and thermonuclear reactors by neutrons with hard spectrum in temperature range from 300 to 1000 °C.

Reactor core may consist of 85 to 124 fuel assemblies. Either uranium dioxide enriched to 90% or a mixture of uranium and plutonium dioxide is used as the fuel composition. Enrichment of uranium is within 45-90%, and the concentration of plutonium reaches 30%. In recent years, the reactor is operating at a power of 53 MW about 220-230 days per year. The time factor of utilization (the ratio of the number of full days of full power operation to the number of days in calendar year) in recent years remained at the level of 0.60-0.65. These data allow to estimate annual U235 consumption. On condition that the discharged fuel burn-up is 30%, annual consumption is up to 39 kg.

The reactor's 20 year design lifetime was already exceeded twofold. The reactor was supposed to be renovated in 2009 with life extension until 2030. However, assessment of the performance of various reactor systems showed that the reconstruction is inappropriate. Therefore it was decided to extend the life of the BOR-60 only for the period from 2010 to 2015. However, the decision was taken recently to extend the operation of the BOR-60 up to 2020, because its use is very important for implementation of the Federal Targeted Program "The new generation for nuclear power technologies for the period 2010-2015 and further to 2020". The operation of BOR-60 will continue until the completion of the construction of a multipurpose fast neutron research reactor (MBIR) which is to be commissioned in 2019 -2020.[11]

Unique characteristics of BOR-60, its use for solving scientific and practical problems, as well as approaching its decommissioning time, exclude the possibility of its conversion.

SM-3 *(NIIAR)*

A high-flux water-cooled water-moderated tank-type SM-3 reactor with a thermal power of 100 MW is designed primarily for production of trans-uranium elements and radioactive isotopes of light elements, as well as for irradiation of reactor materials samples and for studying their properties in the process of irradiation.[12]

The reactor has an extremely compact core consisting of 28 fuel assemblies and with a metal beryllium reflector placed in steel vessel. FA consists of fuel rods having cruciform cross-section. Fuel meat is a composition of 90% uranium dioxide dispersed

[11] "The operation term of BOR-60 will be extended after 2015", Nuclear.Ru, 01.11.2010. http://www.nuclear.ru/rus/press/other_news/2118217/

[12] Golovanov V.N., Yefimov V.N., Klinov A.V., Makhin V.M. "Research Reactors of GNTs RF NIIAR: Main Results of Operation and Use. Proposals on Using for the Development of Nuclear Technologies of XXI Century", International Scientific and Technical Conference "Research Reactors in XXI Century", June 20-23, 2006, Moscow.

in a copper matrix with addition of beryllium bronze. Mass of U235 in FA is 1,128 kg. Average annual fuel consumption is 70 fuel assemblies or 79 kg of U235.[13]

The utilization factor of the reactor is sufficiently high (0.7). The design service life of the reactor is 25 years, until 2017. However, accomplished technological improvements of various reactor systems, as well as the results of calculations and experimental studies allow to talk about the possibility of its further operation beyond design service life.

Currently, work is underway to expand the experimental capabilities of the reactor in order to ensure the possibility of long-term irradiation of large-size samples of materials for NPPs. For this purpose, the amount of fuel in the core has been reduced by increasing of uranium-235 content in the existing fuel rods to 20%. Works to replace the central reactor core were planned for 2012-2014.

According to experts the conversion of reactor to LEU fuel with protection of its characteristics is not possible because of its design features.[14]

RBT-6 *and* ***RBT-10/2*** *(NIIAR)*

RBT-6 and RBT RBT-10/2 are the pool type research reactors designed as neutron sources for irradiating materials in order to investigate changes in their properties as well as for production of sources of radionuclides with the required properties. The reactors are used for research that does not require high rate of neutron fluence, but require the possibility of long-term experiments with high stability of parameters.

The core of RBT-6 consists of 56 spent FAs of SM-3 reactor. Average burnup of fuel assemblies loaded no less than 35%, and the burnup of discharged FAs no less than 50%. The total mass of U235 in the reactor core at the beginning of the campaign is 32-34 kg. The average duration of the campaign is about 40 days.

The RBT-10/2 reactor core consists of 78 spent FAs of SM-3 reactor. Usually, the core is formed mainly of FAs with a burnup of 10÷30%, but not more than 50% burnup of U235. Average burnup of discharged FA is 37-39%. The distillate is used as moderator, and distillate and twelve beryllium cassettes, placed at the corners of the core, as a reflector. The total mass of U235 in the core at the beginning of the irradiation campaign is about 44-46 kg. Duration of campaign is 60 days. The reactor RBT-10/2 is currently operated with 7 MW power, and its utilization factor is 0.6-0.7.

It was assumed that the reactor RBT-6 will be finally stopped in 2009, and the RBT-10/2 – in 2012, but the results of inspection and assessment of their actual state gave grounds for the possibility of further operation until 2020 inclusive.

According to experts' opinion the conversion of the reactor to the use of LEU fuel is impossible.[15] But both reactors can also work with fresh fuel and the design of fuel elements did not exclude the use of fuel composition with higher density. Therefore principal possibility of the conversion exists. On the other hand, if SM-3 reactor will operate until 2017, then the conversion of RBT-6 and RBT-10/2 to low enriched fuel does not seem to be reasonable for economical considerations.

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[13] A.I. Zwir, Yu.A. Krasnov, A.P. Malkov, A.L. Petelin, M.N. Swyatkin, S.I. Chekalkin, "Conversion of SM Reactor to New Fuel During the Process of Current Operation", 13th annual Russian workshop "Safety of Research Nuclear Facilities", Dimitrovgrad, May 23-27, 2011.
[14] V. Ivanov. "Research Reactors in Russia. Status and Prospects for Reducing the Fuel Enrichment", Washington, 2010.
[15] *Ibid.*

MIR-M1 *(NIIAR)*

Pool type reactor with a thermal power of 100 MW is designed to test fuel assemblies, parts of individual fuel rods, and to test fuel assemblies of nuclear power stations operating under different conditions: in normal operation mode, in troubled and accident conditions. The reactor is also used for isotopes production.

The reactor core assembled from hexagonal beryllium blocks and containing from 48 to 58 FAs is placed in a water pool. Each working FA consists of 4 coaxial annular fuel rods with a height of the active part of 1 m. FAs are cooling by circulating water. Fuel meat composition – 90% of uranium dioxide dispersed in aluminum matrix. The fresh fuel assembly contains 356 g of U235, therefore the total mass of U235 in the core loaded by 58 FAs is 20.6 kg. Average burnup of discharged fuel is 55-60%. The utilization factor in recent years was about 0.6, the annual HEU consumption is up to 39.1 kg.[16]

Based on the results of a comprehensive survey of the reactor systems and equipment, conducted in 2001-2003, in 2004 the decision was approved to extend operation of the MIR-M1 up to 2017 under condition of realization of the reactor improvement program. This program provides for modernization of reactor's systems and equipment without long stops of its operation, providing the utilization factor of the reactor usage during the year at the level about 60%.[17]

In accordance with the Russian-American agreement on the preliminary study on the possibility of converting six Russian RRs, the study of possibility of conversion of MIR-M1 to LEU fuel has been accomplished. Preliminary analysis shows that such a possibility exists in the case of development of a 6-tube coaxial FA, with the fuel composition of the 19.7% uranium dioxide dispersed in an aluminum matrix, or 19.7% enriched uranium dispersed in molybdenum.[18]

IBR-2M *(JINR, Dubna)*

The IBR-2 is a fast-neutron sodium-cooled periodically pulsed reactor with average power of 2 MW.[19] The reactor is mainly used for research in condensed matter physics, biology, chemistry and materials science. During the period from 2004 to 2011 reactor was modernized and its operational and physical characteristics were significantly improved. Neutron flux density in the center of the core reaches 10^{17} n/cm^2 sec. In June 2011, the modernized reactor, known as IBR-2M was launched.

The reactor core consists of 69 fuel assemblies, which contain 82.5 kg of plutonium dioxide. The core can be used during 20 years if reactor will operate 2500 hour per year.

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[16] I.T. Tretiyakov, "Modification of the reactors cores", presentation at the Russian-American Symposium on Conversion of the Research Reactors to LEU Fuel, Moscow, June 8-10, 2011.

[17] A.L. Izhutov, V.A. Ovchinnikov, S.V. Romanovsky, V.A. Svistunov, M.N. Svyatkin, "Extension of Service Life and Perspectives of Using of Looping Research Reactor MIR", 13th annual Russian workshop "Safety of Research Nuclear Facilities", Dimitrovgrad, May 23-27, 2011.

[18] V.A.Starkov, "The Status of Testing LEU U-Mo Full Size IRT Type Fuel Elements and Mini-Elements in the MIR Reactor", *Progress, Challenges, and Opportunities for Converting U.S. and Russian Research Reactors: A Workshop Report*, the National Academies Press, Washington D.C. 2012.

[19] Aksenov V.L., Anan'ev V.D., Vinogradov A.V., Shabalin E.P., Tret'yakov I.T. "Modernization of impulse reactor IBR-2", International Scientific and Technical Conference "Research reactors in XXI century", June 20-23, 2006, Moscow.

The unique design of the reactor, a record high neutron flux density, a recent reconstruction and long-term use of the reactor core without reloading (20 years) with high probability exclude it from a list of potential candidates for conversion.

VVR-M *(PINP, Gatchina)*

VVR-M is a pool-type water-cooled reactor with thermal power of 18 MW; it was commissioned in the end of 1959. It is used for studies of nuclear physics, physics of condensed matter, radiation material science, radiobiology, and also for medical and industrial isotope production. During reactor's lifetime its systems were continuously modernized.

The reactor core with beryllium reflector contains 145 of VVR-M5 FA. Fuel composition is 90% enriched uranium dioxide dispersed in aluminum matrix. Each fuel assembly contains 74 g of uranium and total uranium mass in reactor core is equal to 10.73 kg. The duration of reactor operation in powered mode reaches 3000 hours per year.[20] The duration of single working cycle is 35 days, of which 21 days reactor works with 18 MW of power. Burnup of discharged fuel is equal to 29%. Annual U235 consumption, in the case of 10 working cycles per year, is 13 kg.

VVR-M5 fuel assemblies are also manufactured with 36% enrichment. However, research has shown that operational characteristics of VVR-M reactor degrade after the conversion to low enriched fuel. Preservation of the reactor's characteristics requires the use of fuel with uranium density 8.5 g/cm^3, but now such fuel is not produced.[21] Given the fact that the development, testing and licensing of new fuel should require several years and the reactor is quite old, the appropriateness of its conversion to low enriched fuel is not obvious.

PIK *(PINP)*

Physical start-up of high-flux research reactor with a thermal output of 100 MW took place in 2011, and powered start-up is scheduled for 2014.[22] PIK reactor is designed to conduct research in the field of nuclear physics, the physics of weak interaction, condensed matter physics, structural and radiation biology and biophysics, radiation physics and chemistry, as well as for applied engineering problems.

Reactor core has a volume of 50 liters and consists of 18 fuel FAs differing in composition and shape and placed in a heavy-water reflector.[23] Twelve fuel assemblies have irregular hexagonal cross-section and they contain 241 fuel rods with cruciform shape. Six square fuel assemblies contain 161 fuel elements each. Fuel rods of SM reactor with increased length up to 500 mm are used in PIK reactor. The fuel composition is 90% enriched uranium dioxide dispersed in copper-beryllium matrix. Uranium density in the matrix is equal to 1.5 g/cm^3. Total uranium mass in reactor core is estimated as 33 kg.

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[20] Alekhin A.I., Konoplev K.A., Orlov S.P., Pikulik R.G., "46 Years of Operational Expertise of VVR-M PIYaPh RAN Reactor", International Scientific and Technical Conference "Research reactors in XXI century", June 20-23, 2006, Moscow.

[21] I.T. Tretiyakov, "Modification of the Reactors Cores", presentation at the Russian-American Symposium on Conversion of the Research Reactors to LEU Fuel, Moscow, June 8-10, 2011.

[22] "Powered start-up of PIK research reactor may take place in 2014", Nuclear Ru, June 6, 2012, http://www.nuclear.ru/rus/press/other_news/2126561/

[23] Zacharov A.S., Konoplev K.A., Pikulik R.G., Smol'sky S.L., Sushkov P.A., "Study of Start-Up PIK Reactor Core at Full-Scale Critical Test Stand", International Scientific and Technical Conference "Research Reactors in XXI Century", June 20-23, 2006, Moscow.

To estimate the PIK reactor annual consumption of U235 let's assume that power reactor will operate 250 days a year, and the average burn-up of the discharge fuel will be at a level of 30%. Under these assumptions, the annual consumption of U235 will reach 83 kg.

The prospect of conversion to LEU fuel of this reactor with record parameters, given that its construction is carried out intermittently since 1979 and the process of commissioning finally began, looks unlikely now.

IR-8 *(KI)*

IR-8 is an 8 MW power water-pool type reactor with neutron reflector assembled from beryllium blocks and with ordinary water used as moderator, coolant and upper shielding. The reactor possesses experimental capabilities for carrying out fundamental and applied studies in fields of nuclear physics, solid state physics and superconductivity, nano-materials and nano-technologies, radiation chemistry, radiation biology, radiation materials science, testing of fuel composition samples for prospective power reactor facilities, and also for production of different radioisotopes.

IR-8 reactor core consists of sixteen six- and four-tube fuel assemblies IRT-3M with square cross-section. Metal ceramics or uranium-molibdenum alloy can be used as fuel. The mass of 90% enriched uranium in eight-, six- and four-tubes fuel assemblies is equal to 352, 309 and 235 grams respectively. Total mass of U235 in reactor core with fresh fuel assemblies is equal to 4.35 kg and average burnup of discharged fuel is 45%.[24] The duration of single working cycle is equal to 41.7 days and 250 MW-days of energy is produced during this period. Annual number of working cycles is equal to 4 with total duration of powered operation of 4000 hours. Eight fuel assemblies (2.2 kg U235) are consumed per year.

This reactor is one of six RRs for which preliminary study of conversion possibility is carried out in accordance with to Russian-American agreement. Conversion perspectives for this reactor are determined mainly by possibility of maintaining neutron flux at the level of 10^{14} n/cm^{2}s without substantial increase of power. Initial stage of conducted studies did not exclude a possibility of this reactor operation with uranium-molybdenum dispersed fuel composition with 19.7% uranium enrichment.

ARGUS *(KI)*

Water-cooled and water-moderated solution reactor "Argus" with thermal power of 20 kW is used for neutron radiography, neutron activation analysis and for the production of medical isotopes.

The core of the reactor contains 22 liters of aqueous solution of uranylsulfate (UO_2SO_4). The enrichment of uranium is 90%, the mass of uranium – 1.71 kg. During 2006-20010 the reactor was operated less than 10% of calendar time.[25]

Reactor Argus is included on the list of the six RRs for which a preliminary study on the possibility of conversion is carrying out in accordance with the Russian-American agreement. At present, the preparatory work on the conversion of the reactor to low-enriched fuel is going on. It is expected that this work will be completed in 2014.

[24] V. Nasonov, "Conversion of IR-8 reactor", presentation at the Russian-American Symposium on Conversion of the Research Reactors to LEU Fuel, Moscow, June 8-10, 2011.

[25] Svyatkin M.N., Fedulin V.N., Gataullin N.G., Vinogradov M.K., "Analysis of Russian Research Nuclear Facilities Operation in 2006-2010", Center of information collection and analysis on the safety of research nuclear facilities (TsAI IYaU); http://safety.niiar.ru/file/doklad4.doc

OR *(KI)*

Water-water-moderated pool type OR reactor with 300 kW thermal power is intended for fundamental scientific and applied studies on radiation protection and radiation resistance of equipment.

Reactor core contains 25 fuel assemblies of C-36 type. Uranium enrichment is 36%, total uranium mass in the reactor core is equal to 3.8 kg. Annual U235 consumption is estimated as 0.08 kg for 2000 hours powered operation per year.

OR reactor is on the list of six RRs for which preliminary study of conversion possibility is carried out in accordance with Russian-American agreement.

GIDRA *(KI)*

Gidra is a homogenous pulse reactor with 30 MJ pulse energy. It is used for tests of fuel elements for nuclear propulsion reactors, and also for short-lived isotopes production.

Reactor core contains 40 liters volume of aqueous solution of uranilsulfate (UO_2SO_4). Uranium enrichment is 90%, the mass of U235 is equal to 3.2 kg. This reactor was operated in 2006 - 2010 less than 10% from calendar time.

IVV-2M *(IRM in Zarechnyy)*

The high-flux water-cooled water-moderated pool type reactor IVV-2M with a thermal power of 15 MW is used for studies of fuel materials and fuel rods. During 1996-2006 the work on extension of the reactors life until 2025 has been accomplished.

The reactor core is formed by of 42 hexagonal shaped tubular assemblies. The fuel composition is 90% uranium dioxide dispersed in the aluminum matrix. The total mass of U235 in the core is 6.76 kg. Utilization factor is high and reaches 85%. Assuming that the discharged fuel burnup is 45%, the estimated annual consumption of U235 for this reactor should be 9.6 kg.

The initial study on the reactor conversion to LEU fuel has shown that the use of the dispersion fuel with 19.7% uranium enrichment and a density of 6.5 g/cm3 should not lead to deterioration of the reactor characteristics. However, whether the production of these fuels will be economically justified is not clear now. With this in mind, and taking into account possible date of reactor decommissioning (in 10-12 years), as well as the time required for the development and testing of new FAs with low-enriched uranium, the appropriateness of the conversion of the reactor is not clear.

VVR-C *(Karpov Institute in Obninsk)*

VVR-C is a heterogeneous, water-water pool type reactor with a thermal power of 15 MW. It is designed for a wide range of research activities in the field of radiation chemistry, structural and materials research, activation analysis. Since 1980, the reactor is used for medical isotope production, neutron doping of semiconductors, and radiation modification of minerals.

The reactor core contains 70 of VVR-C FAs assembled of three or five tubular rods having a hexagonal shape. The fuel composition is 36% enriched uranium dioxide dispersed in an aluminum matrix. The five-rods FA contains 103 g and the three-rods FA - 89 g of U235. The annual consumption of U235, under assumption that the reactor operates 250 days at a power 13 MWt is 8.1 kg.

The design of the reactor is similar to the Kazakhstan reactor VVR-K, for which the LEU fuel with enrichment of 19.7% is developed. At present, the VVR-KN type FAs, produced at the Novosibirsk Chemical Concentrate Plant, are passing the final test. Conversion of the VVR-K reactor to the new FAs does not affect its operating characteristics. Consequently, the reactor VVR-C can also be converted to LEU fuel with 19.7% enrichment. And since a systematic and consistent upgrading of the VVR-C reactor aimed at creating on its basis of a new IVV-10 reactor is currently under way, conversion to LEU fuel would be advisable. For targets that are irradiated at VVR-C, a plan to convert them from HEU to LEU is currently being formed .[26]

IRT-T *(TPU)*

The IRT-T is water pool-type and its thermal power is 6 MW. The reactor is used for training specialists whose specialization will be design and operation of nuclear facilities, as well as for studying scientific and practical problems in the field of nuclear physics, neutron activation analysis, radiation physics and chemistry, and nuclear medicine. The reactor is also used for contracted work on silicon doping, the income from which is a significant part of the funds necessary to maintain normal operation of the reactor. Since its launch in 1967, the reactor went through several renovations, and its initial power was increased from 2 MW to 6 MW. As a result of the renovations reactor's lifetime is extended up to 2034. Currently, there are plans to increase reactor's power to 12 MW.

Initially the core was loaded with the EC-10 FAs with 10% enrichment. After the reconstruction of the core in 1971 IRT-2M FAs were used, and since 1979 the core has beryllium reflector and uses IRT-3M U-Al alloy FAs with 90% enriched uranium. At present, the core is formed of eight six-rods and twelve eight-rods FAs containing 309 g and 352 g U235 respectively. The total mass of U235 in the core is 6.7 kg. If the average time of reactor's operation at a power is 3,500 hours per year, then the annual consumption of U235 is 2.2 kg.

The IRT-T reactor is on the list of six RRs for which preliminary study of conversion possibility is carried out in accordance with Russian-American agreement. It should be also noted that reconstruction and modernization of IRT-T reactor is included into the list of activities of Federal Targeted Program "Ensuring of Nuclear and Radiation Safety for 2008 and for Period Until 2015". Reactor's owner, Tomsk Polytechnic University in cooperation with the Argonne National Laboratory (USA) examines the possibility of the reactor conversion to LEU fuel. Preliminary results show, that the conversion to low enriched uranium-molibdenum fuel will result in substantial hardening of neutron spectrum, which excludes the possibility of reactor usage for silicon doping.[27]

IRT *(MEPhI)*

The IRT is a water pool-type research reactor that has the power 2.5 MW and is used for scientific research, training of students and re-training of specialists for research centers.

The reactor core consists of sixteen IRT-3M FAs – ten six-rods and six eight-rods. The fuel is UO2 dispersed in aluminum matrix with 90% enriched uranium. The total

[26] "V. Pershukov: Conversion of the Research Reactors to LEU Fuel will Began in 2013", Nuclear Ru, January 10, 2012. http://www.nuclear.ru/rus/press/other_news/2128090/

[27] Yu. A. Tsibulnikov, presentation at the Russian-American Symposium on Conversion of the Research Reactors to LEU Fuel, Moscow, June 8-10, 2011.

mass of U235 in the core is 3.5 kg.[28] Reactor is operated at a power less than 1,000 hours per year, so the annual demand for U235 does not exceed 0.25 kg.

The reactor is also one of the six RRs, which are subjects of a preliminary study on the possibility of conversion that is carried out in accordance with the Russian-American agreement. The results of the initial phase of the study show that although a number of the reactor characteristics will deteriorate, it is possible to convert the reactor for use of IRT-4M FAs with 19.7% enrichment.[29] However, this would require the reconstruction of the reactor, which is scheduled by the Federal Targeted Program "Nuclear and Radiation Safety in 2008 and for the Period up to 2015."[30]

BARS-4 *(NIIP, Lytkarino)*

The BARS-4 is a fast two-core self-extinguishing research reactor that is used as an intense source of gamma and neutron radiation for studies of radiation resistance of electronic equipment and components of nuclear weapons. Average power of the reactor is 1 kW, peak pulse power is $1.4\ 10^8$ kW, and pulse energy is 4 MJ.

The reactor core is formed by 20 FAs of the type R-56, the fuel composition is uranium-molybdenum alloy with 90% HEU. Weight of the core is 250 kg. According to the technical regulations of the reactor, it can produce no more than one pulse per day.

The operation mode of the reactor makes the task of conversion to LEU fuel irrelevant and it is not currently considered.

IRV-M2 *(NIIP, Lytkarino)*

The water pool-type reactor IRV-M1 with a power of 2.0 MW was constructed to conduct research in the field of radiation resistance of materials, electronic products, and electrical engineering. The design of the reflector and the experimental channels ensure the formation of neutron fluxes with hard spectrum needed to perform the tasks assigned to the reactor. From 1991 to the present time the reactor is going through reconstruction, its power will be increased to 4 MW, and the reactor received its current designation IRV-M2.[31]

The reactor core consists of 21 IRT-2M type fuel assemblies, which have four- or three-fuel rods. The fuel composition is cermet using 36% enriched uranium. Mass of U235 in a four-rods FA is 230 g, and in a three-rods FA – 198 g. The total weight of U235 in the core is 4.5 kg. With operation at the nominal power of 2,000 hours per year, the consumption of HEU will be 0.83 kg

Given the fact that the reactor went recently through reconstruction and its core was upgraded, it seems unlikely that a work on the conversion of the reactor to LEU fuel will be initiated in near future.

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[28] A.A. Portnov, "Results of IRT MEPhI Operation in 2008", report at workshop "Safety of Research Nuclear Facilities", Dimitrovgrad, May 2009.

[29] I.T. Tretiyakov, "Modification of the Reactors Cores", presentation at the Russian-American Symposium on Conversion of the Research Reactors to LEU Fuel, Moscow, June 8-10, 2011.

[30] E.F. Krychkov, "Problems of IRT MEPhi Reactor Conversion", presentation at the Russian-American Symposium on Conversion of the Research Reactors to LEU Fuel, Moscow, June 8-10, 2011.

[31] A.M. Chlenov, D.I. Markitan, V.I. Trushkin, V.V. Lemekhov, "Reconstruction of Swimming-Pool Type Research Reactor IRV-M1", International Scientific and Technical Conference "Research reactors in XXI century", June 20-23, 2006, Moscow.

Prospects for the conversion of Russian research reactors

The above review shows that the range of scientific, technical and practical problems solved by research reactors is extremely wide. It includes fundamental research, the development of nuclear energy and the production of medical isotopes and materials for electronics. A wide range of tasks led to a variety of reactor types and their specifications. RRs differ by core design, power output, mode of operation, the cooling system, moderator and reflector materials, and enrichment of the used fuel.

Information about the mass of U235, located in the cores of each of these reactors, as well as evaluation of its annual consumption is given in Table 2.

Table 2. List of Russian RRs Working on HEU Fuel

№	Name	Commissioning / Modernization	Mass of U_{235} in reactor core, kg	Enrichment	Annual consumption of U_{235}, kg (estimate)
1	Argus	1981	1.71[32]	90%	–
2	IR-8	1964/81	4.8[33]	90%	2.2
3	Hydra	1972	3.2[34]	90%	–
4	OR	1954/89	3.8[35]	36%	0.8
5	Bars-4	1982	250[36]	90%	–
6	IBR-2M	1984/2011	82.5[37]	90%	–
7	VVR-M2	1959	13.4[38]	90% (36%)[39]	13
8	SM-3	1961/92	36 (23)[40]	90%	79
9	RBT-6	1975	34	90%	–
10	RBT-10/2	1984	44 (18.4 – 50.7)[41]	90%	–
11	MIR-M1	1966/75	17.95[42]	90%	39.1
12	Bor-60	1969	55 – 90[43]	UO_2 90%, PuO_2	39
13	IVV-2M	1966/82	10.5[44]	90%	9.6

32 V. Ivanov "Research Reactors in Russia. Status and Prospects for Reducing the Fuel Enrichment", Washington, 2010.
33 *Ibid*.
34 V.A. Pavshuk, V.E Khvostionov, "Solution Based Reactors "Hydra" and "Argus"", in "High Temperature Nuclear Energy Technology. Unique Developments and Experimental Base of Kurchatov Institute", http://www.rfbr.ru/rffi/ru/books/o_64092#77
35 See footnote 32.
36 Magda E.P., Snopkov A.A., Kurakov N.P., Levakov B.G., Lukin A.V., "Impulse Nuclear Reactors of RPhYaTs-VNIITF (review)", International Scientific and Technical Conference "Research Reactors in XXI century", June 20-23, 2006, Moscow.
37 Aksenov V.L., Anan'ev V.D., Vinogradov A.V., Shabalin E.P. (OIYaI, Russia), Tret'yakov I.T. (FGUP NIKIET, Russia), "Modernization of Impulse Reactor IBR-2", International Scientific and Technical Conference "Research reactors in XXI century", June 20-23, 2006, Moscow.
38 See footnote 32.
39 See http://www.nccp.ru/ir/vvr-m5.html
40 I.T. Tretiyakov, "Status of Research Reactors in Russia and Prospects for their Development", presentation at the 2-nd International Symposium on Nuclear Energy (ISNE-09), October 26-28, 2009/ Amman, Jordan.
41 See footnote 32.
42 See footnote 32.
43 See http://www.niiar.ru/?q=bor_60_cartogram and http://www.csgi.ru/gi/gi6/02.htm
44 See footnote 32.

14	IRT-T	1967/84	8.8[45]	90%	2.2
15	VVR-Ts	1964	7.6[46]	90%	8.1
16	PIK	2012	33[47]	90%	83
17	IRT	1967	5.15[48]	90%	0.25
18	IRV-M2	1974/2006	4.83[49]	36%	0.83

The data in this Table show that the total amount of U235 contained in the cores of all eighteen reactors reaches 483 kg, and the annual consumption – 276 kg. At the same time the share of seven reactors – IBR-2, SM-3, RBT -6, RBT-10/2, MIR-M1, BOR-60 – of the total HEU annual consumption is about 90%.

These figures essentially characterize the attitude of Russia to the conversion of their RRs to LEU fuel. If the conversion has been a high priority, these seven reactors would have to be the first objects for conversion. However, as noted above, the study of the possibility of conversion to low-enriched fuel is conducted only for one out of seven reactors – MIR-M1, – and preliminary analysis shows that such a possibility is not excluded. However, in the ongoing modernization program of this reactor possibility of its conversion to low-enriched fuel is not considered.[50] An additional indicator of Russia's attitude to this issue can also be a U.S.-Russian agreement on the feasibility study of possible conversion of six Russian RRs. From this list, only the conversion of the MIR-M1 reactor could make a significant contribution to reducing of HEU use, because this reactor is quite extensively used and its annual consumption of U235 is 39 kg. For the remaining five reactors the utilization factor is less than 50%, moreover, for reactors Argus, OR and IRT it is a little more than 10%, and the annual U235 consumption for all five reactors does not exceed 5 kg. Obviously, all this indicates that up to now Russia has given low priority to the problem of conversion of RRs to LEU fuel.

The lack of Russia's interest to the conversion of its own research reactors can be explained by a number of interrelated reasons. As can be seen from Table 2, fourteen of the eighteen RRs are in operation for more than 30 years, and as a result, the utilization factor of RRs is extremely low. In recent years, only a little more than one-third of Russian reactors are used more than half of calendar time, while another one-third is used less than 10% of calendar time. Taking into account economic costs associated with the development, testing and purchase of low-enriched fuel, the owners of the reactors are not interested in their conversion, since they are nearing the end of projected lifetime, and virtually not used.

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45 I.N. Grigorov, O.F. Gusarov, P.N. Khudoleev, Yu.A. Tsybul'nikov, "Experience of IRT-T Nuclear Reactor Operation And Development Strategy", International Scientific and Technical Conference "Research Reactors in XXI century", June 20-23, 2006, Moscow.

46 O.Yu. Kochnov, N.D. Lukin, L.V. Averin, "VVR-Ts Reactor: Experience Of Operation And Development Perspectives", http://www.secnrs.ru/magazine/2008/47/47_03.pdf

47 See footnote 40.

48 E.F. Kryuchkov, presentation at the Russian-American symposium on conversion of research and experimental reactors in Russia and USA to LEU fuel, Moscow, June 09, 2011.

49 A.M. Chlenov, D.I. Markitan, V.I. Trushkin, V.V. Lemekhov, "Reconstruction of Swimming-Pool Type Research Reactor IRV-M1", International Scientific and Technical Conference "Research Reactors in XXI century", June 20-23, 2006, Moscow.

50 A.L. Izhutov, V.A. Ovchinnikov, S.V. Romanovsky, V.A. Svistunov, M.N. Svyatkin, "Extension of Service Life and Perspectives of Using of Looping Research Reactor MIR", 13th annual Russian workshop "Safety of Research Nuclear Facilities", Dimitrovgrad, May 23-27, 2011.

Another reason is related with the fact that RRs are the main tool for the solution of problems generated by nuclear power, especially by its development. In Russia, unlike the United States, there are a number of government programs for nuclear power development, which also include the design and construction of new types of nuclear power reactors, including fast neutron reactors. According to specialists, the development of fast neutron nuclear reactors can not be achieved solely using computational methods and will require research of high-flow RRs with a neutron flux density of the order of 10^{16} n/cm^2 s.[51] For this reason, a new multi-purpose fast neutron research reactor MBIR, start-up of which is scheduled for 2019, will run on HEU fuel. Existing reactors that can provide the neutron flux density close to this value are BOR-60, SM-3, RBT-6, RBT-10/2, MIR-M1, PIK, IBR-2M, VVR-M, IR-8, IVV-2M – all using highly enriched fuel. Converting reactors with unique characteristics and occupying the most prominent place among the objects of the experimental base will require not only the development and testing of LEU fuel, but also reconstruction of the core, which essentially means the creation of new reactors. This work would require time and significant financial expenses, and could adversely affect the realization of accepted programs on nuclear power development. It is important to note also that in accordance with the long-term practice the owners of RRs in Russia had to provide funding to keep reactors in the safe operational state themselves.[52]

Finally, there is also a view that in the context of non-proliferation, conversion of RRs is not so actual for Russia as for other countries, because Russia is a nuclear power.

The absence of a government program for the conversion of Russia's own research reactors, is explaining probably by combination of these factors. Without such a program supported by federal funding it is unreal to count on the interest of the owners of research reactors to conversion.

Low interest to the conversion of its own research reactors however does not reduce the interest of Rosatom to the RRRFR program. The program is an example of a successful U.S.-Russian cooperation, and Russian specialists have expressed interest to including into the program of the HEU spent fuel accumulated at the Russian RRs. The stores accumulated about 14 thousand of FAs and fuel rods of different types, containing several tons of HEU. About 80% of all spent fuel is stored in two plants – IPPE and NIIAR.[53] Currently, Rosatom is collecting and summarizing the information necessary for decision-making to include spent fuel of the Russian RRs into the RRRFR program.

In conclusion, it should be noted that Russia, supporting the final communiqué of the Nuclear Security Summit held in Washington, DC, April 2010, recognizes the urgency of the problem of minimizing of HEU usage and conversion of RRs to LEU fuel. In this context, it seems that that it is advisable for Russia to develop and adopt a governmental program with the main goal of the maintenance and the development of its own fleet of research nuclear facilities capable not only to ensure the solu-

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[51] Progress, Challenges, and Opportunities for Converting U.S. and Russian Research Reactors: A Workshop Report, the National Academies Press, Washington D.C. 2012, www.nap.edu

[52] N. Archangelskiy, "The Mechanism for Financing of the Research Reactors will be Developed to the End of 2013", presentation at the RRFM-2013 Conference, St-Peterburg, April 21-25, 2013. http://www.nuclear.ru/rus/press/other_news/2130362/

[53] Kachur L.I., "Preliminary Studies of the Possibility of the Extension of the International Program on the Return of Spent Fuel of Research Reactors Manufactured in Russian Federation (RRRFR)", 13th annual Russian workshop "Safety of Research Nuclear Facilities", Dimitrovgrad, May 23-27, 2011.

tion of the problems related to nuclear power development and defense technologies, but also meet its international obligations.

It seems that one of the directions of this program would be to conduct audits of all Russian nuclear research facilities. This would make it possible to identify installations, operation of which is inexpedient because of their age and/or the lack of tasks for them, as well as to make decision on the construction of new facilities that can ensure the necessary experimental base to meet the challenges of nuclear power development and complying to modern standard of nuclear safety and non-proliferation.

Such a program must also identify sources of funding needed for decommissioning of unnecessary nuclear research installations, conversion of those RRs for which it is technically feasible and economically justified, and the construction of new research facilities. The adoption of such a government program would indicate clearly that Russia, along with other countries, works in the direction of minimizing the use of HEU in the civilian sector.

August 2, 2013 (corrected on August 23, 2003)