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Prospects for Conversion of HEU-Fueled Research Reactors in Russia

Anatoli S. Diakov

Center for Arms Control, Energy, and Environmental Studies, Dolgoprudny, Moscow

The importance of converting research reactors from highly enriched uranium (HEU) fuel, with enrichment levels as high as 90–93 percent uranium-235, to low-enriched uranium (LEU) fuel, was recognized in the 1970s. Russia has developed and produced fuel enriched to below 20 percent to replace HEU-fuel for research reactors it had supplied to Hungary, Ukraine, Vietnam, the Czech Republic, Uzbekistan, Libya, Bulgaria, and North Korea, but until recently, has not given priority to the task of converting its own research reactors, despite the fact that Russia now has more HEU-fueled research reactors than any other country. In December 2010, Russia and the United States agreed to conduct a preliminary study on the possibility of converting six Russian research reactors. This article assesses the prospects for their conversion.

INTRODUCTION

Nuclear research reactors, including steady state and pulsed reactors, and critical and sub-critical assemblies, offer a source of neutrons and are a unique tool for experimental research in various fields of science and technology. Without them the development of nuclear weapons and nuclear energy would be impossible. Over time, the use of research reactors has been adopted in other sectors such as medicine and biology. The number of research reactors in the world increased rapidly starting in the 1950s and reached a maximum of 390 in the 1970s.[1] According to the International Atomic Energy Agency, as of mid-2014, more than 747 research reactors, critical and subcritical assemblies of different types and different capacities, have been built.[2] By the early 1980s the growth in the number of nuclear research reactors in the world had stopped.

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Address correspondence to Anatoli S. Diakov, Center for Arms Control, Energy and Environmental Studies, 3 Zhukovskogo Street, #301, Dolgoprudny, Moscow Region, 141700, Russia. E-mail: diakov@armscontrol.ru
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The most powerful research reactors had achieved a neutron flux density of 0.5 $\times 10^{15}$ n/cm^2 per second, and attempts to increase flux density beyond these limits ran into problems due to the instability of reactor materials. Solving this materials science problem required significant research and funding. By this time, however, large amounts of experimental data had been accumulated which allowed for the development and verification of computer programs to solve many research problems through calculation and modeling rather than by experimentation. As a result, construction of new research reactors has virtually ceased and increasing numbers of reactors are being decommissioned. As of mid-2014, there were 247 active research reactors worldwide, with only 6 under construction and 12 planned, while 143 are shut down and 338 decommissioned.[3]

The principal characteristic of a research reactor is the ratio of the neutron flux density to the reactor power. A priority for researchers and designers has been to maximize the neutron flux density available in experimental channels while minimizing reactor power. Achieving this goal has traditionally required a small core fueled with uranium at the highest possible enrichment level. For this reason, the majority of research reactors in Russia and in the United States were designed to be fueled with HEU, enriched to 90–93 percent uranium-235, a level typically reserved for nuclear weapons.[4]

In the late 1970s, both in the United States and the Soviet Union, it was recognized that using HEU in civilian research reactors, especially where the fuel was exported to other countries, created proliferation risks. To counter these risks both countries initiated programs to lower the enrichment level of fuel supplied to other countries from 80–90 percent to 20–36 percent uranium-235. The two-stage Soviet program to reduce fuel enrichment in research reactors was adopted in the early 1980s[5]: the first stage reduced the enrichment level to 36 percent, the second—to below 20 percent.

In 1993, Russia and the United States began collaborating on the development of low-enriched fuel (less than 20 percent) for research reactors supplied by Russia (USSR) abroad. This ongoing program is part of the Reduced Enrichment in Research and Test Reactors program (RERTR).

In 1994, the Ministry of Atomic Energy of the Russian Federation initiated the program "Creation of fuel rods and fuel assemblies with fuel enriched to 20 percent uranium-235 for the cores of research reactors."[6] The main goal of the program is the development and organization of the production of fuel assemblies for Soviet- supplied reactors in third countries. This program participants include TVEL Fuel Company (JSC TVEL), N. A. Dollezhal Research and Development Institute of Power Engineering (JSC NIKIET), A. A. Bochvar All-Russian Scientific Research Institute for Inorganic Materials (VNIINM), Novosibirsk Chemical Concentrate Plant (JSC NCCP), Scientific Research Institute of Atomic Reactors (JSC State Scientific Center - NIIAR), A.I. Leipunski Institute of Physics and Power Engineering (IPPE), Institute of

Reactor Materials (JSC IRM), National Research Center Kurchatov Institute (NRC KI), and the V.P. Konstantinov Petersburg Nuclear Physics Institute. The program had three phases:

1. Development of fuel rods and fuel assemblies with fuel using UO_2-Al.
2. Development of fuel rods and fuel assemblies with high-density fuel based on uranium-molybdenum alloys.
3. Development of fuel rods and fuel assemblies for the new generation of research reactors.

As of 2006, the work on the first phase had been practically completed. The production of fuel assemblies VVR-M2 and IRT-4M with enrichment below 20 percent was initiated at the Novosibirsk Chemical Concentrate Plant for research reactors supplied to Hungary, Ukraine, Vietnam, the Czech Republic, Uzbekistan, Libya, Bulgaria, and North Korea.

The success of the first phase laid the foundation for the May 2004 United States-Russian agreement on fuel removal and repatriation and the Russian Research Reactor Fuel Return Program (RRRFR program). This gave a boost to the efforts to remove Russian-made fresh and spent HEU fuel from third countries to Russia and convert those research reactors to LEU fuel. Fourteen countries participated in the program: Belarus, Bulgaria, Czech Republic, Hungary, Germany, Kazakhstan, Latvia, Libya, Poland, Romania, Serbia, Ukraine, Uzbekistan, and Vietnam.

Approximately 1,930 kg of fresh and spent HEU fuel was returned to the Russian Federation by the end of 2012.[7] The entire stockpile of HEU fuel was removed from Latvia, Bulgaria, Romania, Libya, Serbia, Ukraine, and Vietnam.[8] It is important to note that United States-Russian cooperation on research reactor conversion and return of fresh and spent HEU fuel was supported by joint statements of Russian and U.S. presidents Vladimir Putin and George W. Bush in 2005, and Dmitry Medvedev and Barack Obama in 2009.

Despite the fact that Russia has the largest number of HEU-fueled research reactors inside its borders, the task of converting Russian reactors to LEU fuel was not considered until very recently. Discussions among Russian experts started in connection with the December 2010 Agreement between Rosatom and the U.S. Department of Energy to conduct a preliminary study on the possibility of converting six Russian research reactors: Argus, OR, and I-8 at the Kurchatov Institute (Moscow), IRT-MEPhI (Moscow Institute of Physics and Engineering), IRT-T (Tomsk Technical University), and MIR-M1 (Research Institute of Atomic Reactors, Dimitrovgrad).[9] The data on this program presented in this article is based on available information about the current status of the civilian research reactors and plans for their use.[10]

Russia's Research Reactor Fleet

At the end of 2013, there were 30 research reactors in Russia not including the reactors belonging to VNIIEF and VNIITF, which are used in defense programs. The possibility and necessity of conversion of each civilian reactor is determined by its purpose, core design, and plans for its future use (see Appendix, Russian Civilian Research Reactors).

According to Russian Federal Service for Ecological, Technological, and Nuclear Supervision data for 2013, of the 30 civilian research reactors in the country, only 20 had operating licenses. Seven reactors had decommissioning licenses or are in the final stages of shutdown (MR, RBT-10-1, Arbus, BR-10, AM-1, BARS-6 and TVR). One reactor (IRV-M2) has a construction license, and two reactors (IRT-MEPhI, Gamma-KI) are unlicensed. A previous license for IRT MEPhI has expired and an application for a new license had not been submitted.

The fuel for the IBR-2M pulse reactor is produced from plutonium oxide and two others (IR-50 and VK-50) use LEU fuel. Therefore, there are only fifteen licensed research reactors fueled by HEU, one HEU-fueled reactor with a construction license (IRV-M2) and one whose license application has not yet been submitted (IRT-MEPhI). These reactors are described below.

BOR-60: Research Institute of Atomic Reactors (NIIAR), Dimitrovgrad

BOR-60 is designed to test fuel elements with different compositions containing plutonium; it was commissioned in 1969. It is a large sodium-cooled experimental fast reactor with a thermal power of 60 MW. It is also used for engineering and safety studies to support the development of sodium-cooled fast neutron reactors and for irradiation of structural materials for nuclear and thermonuclear reactors by neutrons with hard spectrum in the temperature range 300 to 1000 °C.

The reactor core may consist of 85 to 124 fuel assemblies, with fuel composed of either uranium dioxide enriched to 90 percent or a mixture of uranium and plutonium. The uranium enrichment is in the range 45–90 percent and the concentration of plutonium reaches 30 percent. In recent years, the reactor has operated at a power of 53 MW for 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 the calendar year) has recently been in the range of 0.60–0.65. Assuming a discharged fuel burn-up of 30 percent, annual uranium-235 consumption is estimated to be up to 39 kg.

The 20 years design lifetime of the reactor has been exceeded twice. In 2009, the reactor was supposed to be renovated and the life extended until 2030. However, an assessment of the performance of various reactor systems showed that the planned reconstruction was inappropriate and it was decided to extend the life of the BOR-60 only for the period from 2010 to 2015. However, in 2010 the decision was made to extend the operation of the BOR-60 to 2020, because it was seen as critical for realizing the goals of the Federal Targeted Program, "The New Generation for Nuclear Power Technologies for the Period 2010–2015 and Further to 2020." BOR-60 is expected to operate until the completion of the multipurpose fast neutron research reactor (MBIR) which is to be commissioned in 2019–2020.[11]

The unique characteristics of BOR-60, the scientific and practical problems that can be studied with it, and its decommissioning timeline exclude the possibility of converting it to LEU fuel.

SM-3: Research Institute of Atomic Reactors (NIIAR), Dimitrovgrad

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

The reactor has an extremely compact core consisting of 28 fuel assemblies and a metal beryllium reflector in a steel vessel. The fuel assemblies consist of fuel rods with a cruciform cross-section. The fuel meat is 90 percent uranium dioxide dispersed in a copper matrix with added beryllium bronze. The mass of uranium-235 in each fuel assembly is 1.128 kg and the average annual fuel consumption is 70 fuel assemblies or 79 kg of uranium-235.[13]

The utilization factor of the reactor is high, at about 0.7. The design service life of the reactor is 25 years and runs until 2017. However, technical improvements of various reactor systems and experimental studies may allow operation beyond its design service life.

The work on expanding the experimental capabilities of the reactor is continuing in order to allow long-term irradiation of large-size samples of materials for nuclear power plants. For this purpose, the content of uranium-235 in the fuel rods was increased from 5 to 6 grams. Work to replace the reactor core is reported to be underway (Figure 1).[14]

Russian research reactor experts believe that the SM-3 cannot be converted to LEU fuel and still maintain its key operating characteristics, and the reactor is unlikely to be converted.[15]

RBT-6 and RBT-10/2: Research Institute of Atomic Reactors (NIIAR), Dimitrovgrad

RBT-6 and RBT-10/2 are 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 radionuclides. The reactors are used

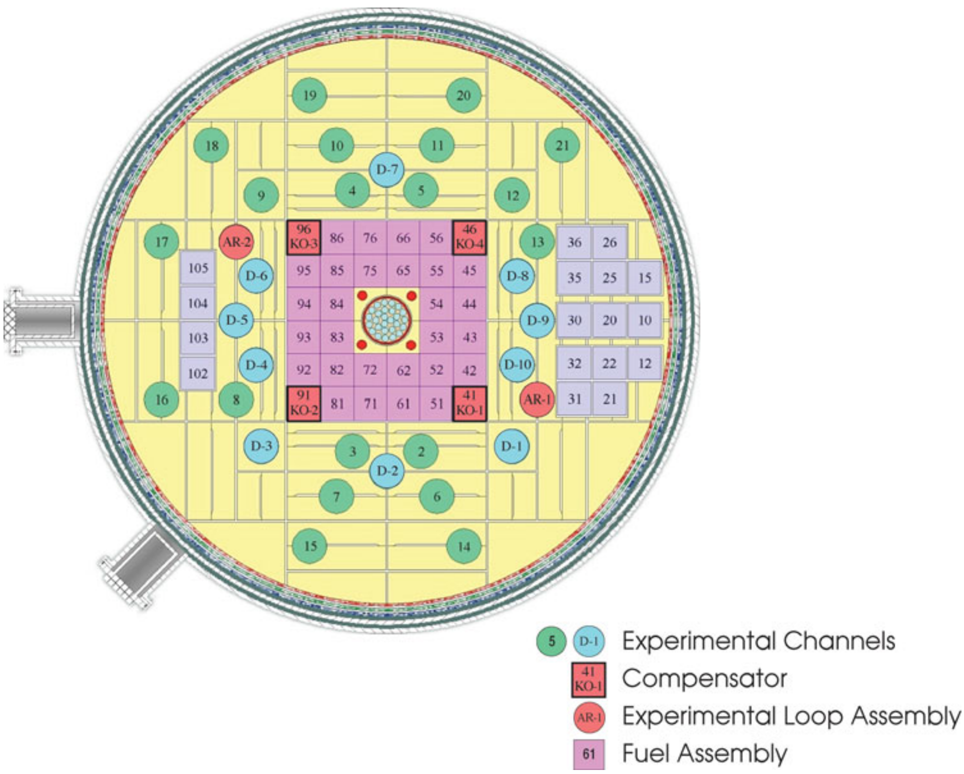


Figure 1: Schematic map of the active core of SM-3 reactor.

for research that does not require high neutron fluence but requires that its neutron flux parameters remain stable over the long term.

The core of RBT-6 consists of 56 spent fuel assemblies of the SM-3 reactor. The average burnup of loaded fuel assemblies is not less than 35 percent, and the burnup of discharged fuel assemblies is not less than 50 percent. The total mass of uranium-235 in the reactor core at the beginning of a campaign is 32–34 kg. The average duration of a campaign is about 40 days.

The RBT-10/2 reactor core consists of 78 spent fuel assemblies of the SM-3 reactor. Usually, the core is formed from fuel assemblies with a burnup of 10–30 percent, but not more than 50 percent. The average burnup of discharged fuel assemblies is 37–39 percent. Very pure distilled water is used as moderator. The distilled water and twelve beryllium cassettes, placed at the corners of the core, act as a reflector. The total mass of uranium-235 in the core at the beginning of the irradiation campaign is about 44–46 kg; the duration of each campaign is 60 days. The reactor RBT-10/2 was operated with 7 MW power, and its utilization factor is 0.6–0.7.

It was assumed that the reactor RBT-6 would be stopped in 2009, and the RBT-10/2 in 2012, but the results of inspection and assessment of their actual state carried during 2007–2011 gave grounds to prolong operations until the end of 2020.

According to Russian experts, converting the reactor to LEU fuel is impossible.[16] However, since both reactors can also operate with fresh fuel and the design of fuel elements does not exclude the use of higher density fuel, the possibility of conversion exists in principle. On the other hand, if the SM-3 reactor operates until 2017 then the conversion of RBT-6 and RBT-10/2 to LEU fuel would not appear to be economically feasible.

MIR-M1: Research Institute of Atomic Reactors (NIIAR), Dimitrovgrad

MIR-M1 is a pool-type reactor with a thermal power of 100 MW. It is designed to test fuel assemblies, parts of individual fuel rods, and fuel assemblies of nuclear power reactors in normal operation mode, in troubled, and in accident conditions. The reactor is also used for isotope production.

The reactor core is assembled from hexagonal beryllium blocks and contains 48 to 58 fuel assemblies in a water pool. Each working fuel assembly consists of 4 coaxial annular fuel rods with the active part reaching a height of 1 meter. The fuel is cooled by circulating water. The fuel meat is composed of 90 percent uranium dioxide dispersed in an aluminum matrix. The fresh fuel assembly contains 356 g uranium-235, and thus a total mass of uranium-235 in a fully loaded core (58 assemblies) is 20.6 kg. The average burnup of the discharged fuel is 55–60 percent. The utilization factor in recent years was about 0.6, and the annual HEU consumption was up to 39.1 kg.[17]

Based on the results of a comprehensive survey in 2001–2003 of the reactor systems and equipment, it was decided in 2004 to extend operation of the MIR-M1 to 2017 subject to completion of a reactor improvement program. This program provides for modernization of reactor systems and equipment without long interruptions in operations, enabling an annual reactor utilization factor of about 60 percent.[18]

The possibility of converting MIR-M1 to LEU fuel was considered as part of the 2010 Russian-United States agreement. Preliminary analysis showed that conversion was possible with the development of a 6-tube coaxial fuel assembly with 19.7 percent enriched uranium dioxide dispersed in an aluminum matrix, or uranium-molybdenum alloy containing 9 wt% molybdenum (U-9Mo) particles dispersed in aluminum matrix.[19]

VVR-M: Petersburg Nuclear Physics Institute, Gatchina

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

The reactor core has a beryllium reflector and contains 145 VVR-M5 fuel assemblies. The fuel composition is 90 percent enriched uranium dioxide dispersed in an aluminum matrix. Each fuel assembly contains 74 g of uranium and total uranium mass in the reactor core is equal to 10.73 kg. The reactor operates in a powered mode for up to 3,000 hours per year.[20] The duration of a single working cycle is 35 days. During 21 of the 35 day cycle, the reactor operates at 18 MW power. The burnup of discharged fuel is 29 percent. Uranium-235 consumption during the 10 annual working cycles is 13 kg.

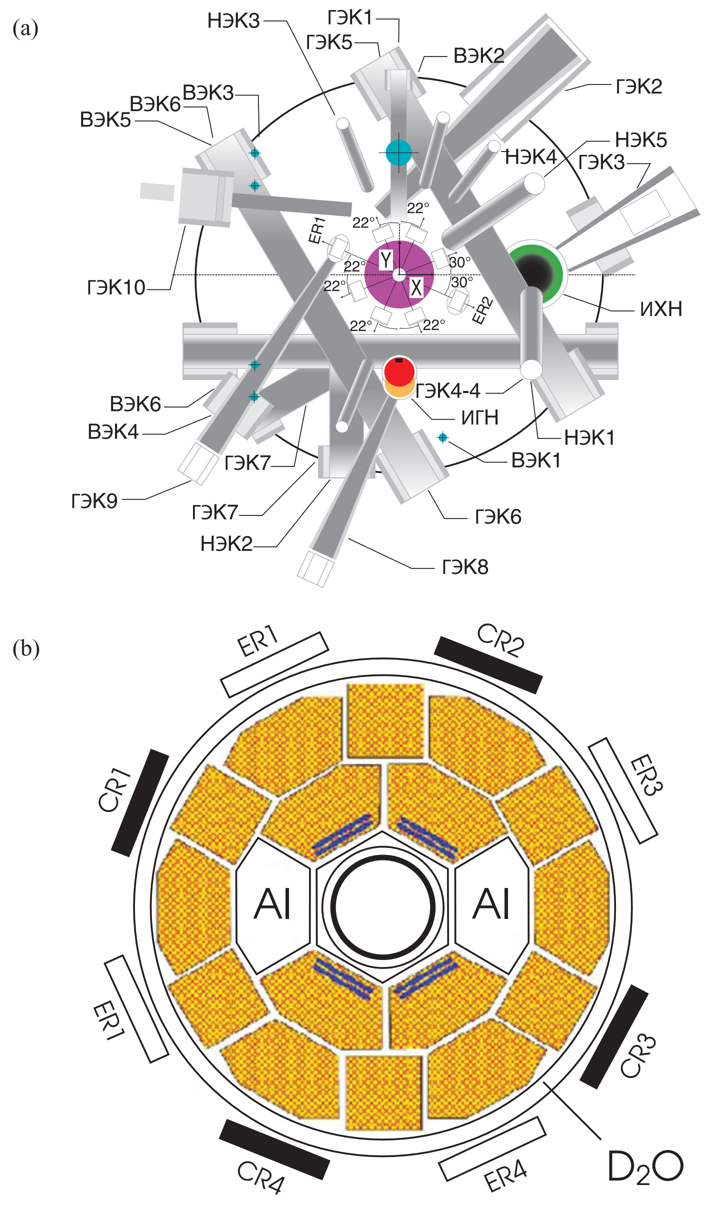
VVR-M5 fuel assemblies are also manufactured with 36 percent enrichment. Calculations have shown that the operational characteristics of the VVR-M reactor could be preserved after the conversion to fuel with an enrichment of 19.7 percent. However, the production of fuel at this enrichment level requires a uranium density of 8.5 g/cm^3 in the fuel meat which is not available yet.[21] Given the fact that the development, testing and licensing of new fuel would require several years and the reactor is quite old, the value of converting the VVR-M to low enriched fuel is not obvious.

PIK: Petersburg Nuclear Physics Institute, Gatchina

PIK is a high-flux research reactor with a thermal output of 100 MW that began operating in 2011, but powered start-up, scheduled for 2014, has been delayed.[22] The 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, and applied engineering.

The reactor core consists of 18 fuel assemblies differing in composition and shape in a heavy-water reflector (Figure 2).[23] Twelve fuel assemblies have irregular hexagonal cross-sections containing 241 fuel rods with cruciform shape. Six square fuel assemblies contain 161 fuel elements each. The PIK reactor uses fuel rods of the SM reactor design with the length increased by as much as 500 mm. The fuel composition is 90 percent enriched uranium dioxide dispersed in copper-beryllium matrix. Uranium density in the matrix is equal to 1.4–1.5 g/cm^3. The total uranium-235 mass in the reactor core is estimated at 27.5 kg. Assuming that the PIK reactor will operate 250 days per year, and an average burn-up of the discharged fuel of 30 percent, the annual consumption of uranium-235 will reach 83 kg.

Given that its construction started in 1979 and the process of commissioning has finally began, the prospect of conversion of this reactor to LEU fuel appears unlikely.



ГЭКnn	Horizontal experimental channel nn	ИГН	Hot neutron source
ВЭКnn	Vertical experimental channel nn	Al	Aluminum
НЭКnn	Inclined experimental channel nn	ERnn	Emergency rods
ИХН	Cold neutron source	CRnn	Control rods

Figure 2: Schematic map of the experimental channels (a) and core (b) of PIK reactor.

IR-8: National Research Centre Kurchatov Institute, Moscow

IR-8 is an 8 MW water-pool type reactor with a neutron reflector assembled from beryllium blocks which uses ordinary water as moderator, coolant, and upper shielding. The reactor provides experimental capabilities for fundamental and applied studies in nuclear physics, solid state physics and superconductivity, nanomaterials and nanotechnologies, radiation chemistry, radiation biology, radiation materials science, testing of fuel composition samples for prospective power reactor facilities, and for the production of radioisotopes.

The IR-8 reactor core consists of sixteen six-tube and four-tube fuel assemblies with a square cross-section. Uranium metal-ceramic or uranium-molybdenum alloy can be used as a fuel meat. The mass of 90 percent enriched uranium in eight-, six- and four-tube fuel assemblies is equal to 352, 309 and 235 grams respectively. The total mass of uranium-235 in the reactor core with fresh fuel assemblies is equal to 4.35 kg and the average burnup of discharged fuel is 45 percent.[24] A single working cycle is 41.7 days and 250 MW-days of energy is produced during this period. There are four working cycles per year, with a total of 4,000 hours of powered operation. Eight fuel assemblies (2.2 kg uranium-235) are consumed per year.

This reactor is one of the six research reactors for which a preliminary study of conversion potential was carried out according to the 2010 Russia-United States agreement. The conversion parameters are defined mainly by the possibility of maintaining neutron flux at the level of 10^{14} n/cm^{2}s without a substantial increase of power. Initial studies did not exclude the possibility of operating this reactor with uranium-molybdenum dispersed fuel enriched to 19.7 percent.

ARGUS: National Research Centre Kurchatov Institute, Moscow

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

The core of the reactor contains 22 liters of an aqueous solution of uranyl sulfate (UO_2SO_4). The uranium is enriched to 90 percent, and the mass of uranium is 1.71 kg. During 2006–2010 the reactor operated less than 10 percent of the time.[25]

The Argus reactor is included in the list of the six research reactors for which a preliminary study on conversion was carried out in accordance with 2010 agreement. It is expected that the conversion to low-enriched fuel will be completed by the end of 2014.

OR: National Research Centre Kurchatov Institute, Moscow

The water-moderated pool type OR reactor with a thermal power of 300 kW was intended for fundamental scientific and applied studies on radiation protection and radiation resistance of equipment. The reactor core contains 25 fuel assemblies of the C-36 type. The uranium is enriched to 36 percent and the total uranium mass in the reactor core is 3.8 kg. Annual uranium-235 consumption is estimated as 0.08 kg for 2,000 hours of powered operation per year. The OR reactor is on the list of six reactors studied for possible conversion.

GIDRA: National Research Centre Kurchatov Institute, Moscow

GIDRA is a homogenous pulsed reactor with 30 MJ pulse energy. It is used to test fuel elements for nuclear propulsion reactors and to produce short-lived isotopes.

The reactor core contains 40 liters volume of an aqueous solution of uranyl-sulfate (UO_2SO_4). The uranium is enriched to 90 percent; the mass of uranium-235 is equal to 3.2 kg. For the period 2006–2010, GIDRA operated less than 10 percent of the time. The Federal Program "Nuclear and Radiation Safety in 2008 and through 2015" called for its decommissioning.[26]

IVV-2M: Institute of Reactor Materials (IRM), Zarechnyy

IVV-2M is a high-flux water-cooled water-moderated pool-type reactor with a thermal power of 15 MW that is used to study fuel materials and fuel rods. During 1996–2006 work was completed to extend reactor life until 2025.

The reactor core is formed from 42 hexagonal tubular assemblies. The fuel composition is 90 percent enriched uranium dioxide dispersed in the aluminum matrix. The total mass of uranium-235 in the core is 6.76 kg. The utilization factor has reached 85 percent. Assuming that the discharged fuel burnup is 45 percent, the estimated annual consumption of uranium-235 is 9.6 kg.

The initial study of conversion to LEU fuel has shown that the use of dispersion fuel with 19.7 percent enriched uranium and a density of 6.5 g/cm^3 would not lead to a reduction of reactor characteristics. However, it has not been determined if these fuels can be produced economically. This and the fact that the reactor may be decommissioned in 10–12 years, coupled with the long lead time for developing and testing new fuel assemblies makes the value of converting the reactor unclear.

VVR-C: Karpov Scientific Research Institute of Physical Chemistry, Obninsk

VVR-C is a heterogeneous, 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, and activation analysis. Since 1980, the reactor has been used to produce medical isotopes, for neutron doping of semiconductors, and radiation modification of minerals.

The reactor core contains 70 VVR-C fuel assemblies, which have three or five tubular rods with a hexagonal shape. The fuel is 36 percent enriched uranium dioxide dispersed in an aluminum matrix. The five-rod fuel assemblies contain 103 g of uranium-235 and the three-rod assemblies contain 89 g of uranium-235. The annual consumption of uranium-235, assuming that the reactor operates 250 days at a power of 13 MWt, is 8.1 kg.

The design of the reactor is similar to the Kazakhstan reactor VVR-K, for which LEU fuel with an enrichment of 19.7 percent has already been developed. Testing of the new fuel assemblies (known as VVR-KN) produced at the Novosibirsk Chemical Concentrate Plant started in 2012. Conversion of the VVR-K reactor to the new fuel assemblies will not affect its operating characteristics. The availability of LEU fuel opens a possibility of the reactor conversion. VVR-C is also involved in production of medical isotopes, the work to convert to LEU targets began in 2013.[27]

IRT-T: Tomsk Polytechnic Institute, Tomsk

The IRT-T is a water pool-type with a thermal power of 6 MW. The reactor is used for training in the design and operation of nuclear facilities, for studies in nuclear physics, neutron activation analysis, radiation physics and chemistry, and nuclear medicine. The reactor is also used for silicon doping, the income from which provides the majority of the funding necessary to maintain the normal operation of the reactor. Since its launch in 1967, the reactor has undergone several upgrades, and its initial power has been increased from 2 MW to 6 MW and the reactor's life time has been extended up to 2034. Plans exist to increase the reactor power to 12 MW.

Initially the core was loaded with EC-10 fuel assemblies with 10 percent enrichment. After the reconstruction of the core in 1971, it was modified to use IRT-2M fuel assemblies, and since 1979 the core has had a beryllium reflector and uses IRT-3M uranium-aluminum alloy fuel assemblies with 90 percent enriched uranium. The core is formed of eight six-rod assemblies and twelve eight-rod assemblies containing 309 g and 352 g of uranium-235 respectively. The total mass of uranium-235 in the core is 6.7 kg. At an average of 3,500 hours per year of full power operation, the annual consumption of uranium-235 is 2.2 kg.

The IRT-T reactor is one of the six research reactors identified for possible conversion. It is also worth noting that the reconstruction and modernization of the IRT-T reactor was included in the list of activities under the Federal Targeted Program "Nuclear and Radiation Safety in 2008 and through 2015." In cooperation with the U.S. Argonne National Laboratory, the reactor's owner, Tomsk Polytechnic University, has examined the feasibility of conversion to LEU fuel. Preliminary results show that the conversion to low-enriched uranium-molybdenum fuel would result in substantial hardening of the neutron spectrum, which would exclude its use for silicon doping.[28] As a result the operator lacks the incentive to convert the reactor.

IRT: Moscow Institute of Physics and Engineering (MEPhI), Moscow

The IRT is a 2.5 MW water pool-type research reactor that is used for scientific research and training. The reactor core consists of sixteen IRT-3M fuel assemblies (ten assemblies with six fuel rods and six assemblies with eight fuel rods). The fuel is a uranium-aluminum alloy with 90 percent enriched uranium. The total mass of uranium-235 in the core is 3.5 kg.[29] The reactor operates at power for less than 1,000 hours per year and the annual demand for uranium-235 does not exceed 0.25 kg.

The reactor is one of the six research reactors that underwent preliminary studies on the possibility for conversion. The results of the initial phase of the study showed that although a number of the reactor characteristics will deteriorate, it is possible to convert the reactor to IRT-4M fuel assemblies with 19.7 percent enrichment.[30] However, the reactor's operators believe that the use of IRT-3M fuel assemblies with U-9Mo dispersed in aluminum is a more promising.[31] In any case, conversion will require the reconstruction of the reactor, which was scheduled is part of the Russian Federal Targeted Program "Nuclear and Radiation Safety 2008–2015."

BARS-4: Scientific Research Institute for Instruments (NIIP), Lytkarino

BARS-4 is a two-core self-extinguishing pulsed fast reactor that is used as an intense source of gamma and neutron radiation for studies of radiation resistance of electronic equipment. The average reactor power is 1 kW, with peak pulse power of 1.4 10^8 kW, and pulse energy of 4 MJ.

The reactor core is formed from 20 R-56 type fuel assemblies, with the fuel composed of uranium-molybdenum alloy with 90 percent enriched HEU. The weight of the core is 250 kg. According to technical regulations, the reactor can produce no more than one pulse per day. Due to its operating characteristics, the fuel has little or no burnup. It makes conversion to LEU fuel irrelevant and is not currently under consideration for conversion.

IRV-M2: Scientific Research Institute for Instruments (NIIP), Lytkarino

The 2 MW IRV-M1 is a water pool-type reactor that was constructed to conduct research on radiation resistance of materials, electronic products, and for electrical engineering studies. The design of the reflector and the experimental channels ensure a neutron flux with the hard spectrum needed to perform the assigned tasks. The reactor was reconstructed after 1991, its power increased to 4 MW, and the reactor was renamed IRV-M2.[32]

The reactor core consists of 21 IRT-2M type fuel assemblies which have three or four fuel rods each. The fuel composition is cermet with 36 percent enriched uranium. The mass of uranium-235 in a four-rod fuel assembly is 230 g, and 198 g in a three-rod assembly. The total weight of uranium-235 in the core is 4.5 kg. Operating at nominal power for 2,000 hours per year, the consumption of HEU would be 0.83 kg.

Given the fact that the reactor was recently reconstructed and its core was upgraded, it seems unlikely to be considered a candidate for conversion to LEU fuel in the near future.

Prospects for the Conversion of Russian Research Reactors

The preceding review illustrates that research reactors are employed across a wide range of scientific, technical and practical applications from fundamental research to the development of nuclear energy and the production of medical isotopes and materials for electronics. The range of tasks has led to a variety of reactor types and specifications, and thus the research reactors differ by core design, power output, mode of operation, cooling system, moderator and reflector materials, and fuel enrichment. Table 1 lists the mass of uranium-235 in the cores of each of the reactors discussed above, as well as an assessment of the annual consumption of uranium-235.

The data in the Table show that the total amount of uranium-235 contained in the cores of all seventeen reactors is about 566 kg, and annual uranium consumption could reach 276 kg (assuming the operation of the PIK reactor at full capacity). Six reactors (SM-3, RBT -6, RBT-10/2, MIR-M1, BOR-60 and PIK) are responsible for about 90 percent of the total annual consumption of HEU.

While it is reasonable to expect that these six reactors would be the primary candidates for conversion, only one, MIR-M1, was considered for study. SM-3 and PIK use a unique fuel and developing a suitable LEU fuel for these reactors would be very difficult. The BOR-60 cannot use LEU fuel in a uranium-fueled core because it is too small to go critical. For these reasons, the conversion of BOR-60, SM-3 and PIK has not been considered.

Russia's approach to research reactor conversion, reflected in the 2010 U.S.-Russian agreement to do a preliminary study of converting six reactors, is based on the availability of suitable LEU fuel. From the list of the six reactors that were part of the joint U.S.-Russian study, only the conversion of the MIR-M1 reactor could make a significant contribution towards reducing the use of HEU and preliminary analysis shows conversion is technically feasible. However, in the ongoing modernization of this reactor, conversion to low-enriched fuel was not considered.[33] For the remaining five reactors the utilization factor is less than 50 percent, and little more than 10 percent for the Argus, OR and IRT reactors. The annual uranium-235 consumption for all five reactors does not exceed 5 kg. These factors have contributed to the low priority Russia has given to converting its research reactors to LEU fuel.

The lack of interest on Russia's part in the conversion of its own research reactors can be explained by a number of interrelated reasons. As can be seen in Table 1, fourteen of the seventeen HEU-fueled research reactors have been

Table 1: Russian Research Reactors with HEU fuel.

Name	Date of commissioning or modernization	Mass of uranium-235 in reactor core (kg)	Enrichment (percent)	Annual consumption of uranium-235, kg (estimate)
Argus	1981	1.71[1]	90	—
IR-8	1964/1981	4.8[2]	90	2.2
GIDRA	1972	3.2[3]	90	—
OR	1954/1989	3.8[4]	36	0.08
Bars-4	1982	250[5]	90	—
VVR-M2	1959	13.4[6]	90 (36)[7]	13
SM-3	1961/1992	36 (23)[8]	90	79
RBT-6	1975	34	90	—
RBT-10/2	1984	44 (18.4–50.7)[9]	90	—
MIR-M1	1966/1975	17.95[10]	90	39.1
Bor-60	1969	55–90[11]	90 (or Pu)	39
IVV-2M	1966/1982	10.5[12]	90	9.6
IRT-T	1967/1984	8.8[13]	90	2.2
VVR-Ts	1964	7.6[14]	90	8.1
PIK	2012	30[15]	90	83
IRT	1967	5.15[16]	90	0.25
IRV-M2	1974/2006	4.83[17]	36	0.83

Note. *Indicates that the reactor was studied for possible conversion according to the agreement between Rosatom and U.S. Department of Energy

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operating for more than 30 years. The utilization factor of some reactors is extremely low. In recent years, only slightly more than one-third of Russian research reactors were used more than half of the time, while another third were used less than 10 percent of the time. Taking into account the economic costs associated with the development, testing, and purchase of low-enriched fuel, the owners of the reactors are not interested in converting reactors which are rarely used and nearing the end of their projected life.

Another reason is related to the fact that the research reactors which operate more frequently are the main research tool supporting nuclear power development. In Russia, unlike the United States, there are a number of government programs promoting nuclear power, which also include the design and construction of new types of nuclear power reactors, including fast neutron reactors. According to Russian experts, the development of fast neutron nuclear reactors cannot be achieved solely on the basis of computer simulations but require research reactors able to generate a neutron flux density of the order of 10^{16} n/cm^2.[34] For this reason, a new multi-purpose fast neutron research reactor MBIR, scheduled to start-up in 2019, is fueled with HEU. Existing reactors that can provide a neutron flux density close to this value are BOR-60, SM-3, RBT-6, RBT-10/2, MIR-M1, PIK, VVR-M, IR-8, IVV-2M, all of which use highly enriched fuel. Converting some of these reactors, which have unique characteristics and important experimental capabilities, is not possible.

Conversion of other reactors will require not only the development and testing of LEU fuel, but also the reconstruction of the cores, which is equivalent to creating a new reactor. This work would require time and significant financial expense, and could adversely affect the success of ongoing nuclear power development programs. Conversion activity would have to be financed by reactor operators, who may not have the necessary resources.[35]

Finally, there is also the view among Russian policy makers that in the context of non-proliferation, conversion of domestic research reactors is a lower priority for Russia because it is a nuclear weapon state.

The absence of a government program for the conversion of Russia's research reactors may be explained by a combination of these factors. Without a program supported by federal funding, it is unrealistic to rely on reactors owners to initiate and fund research reactor conversion.

Low interest in the conversion of its own research reactors is not reflected in the interest of Rosatom in the RRRFR program and the agreement on RRRFR was recently extended to 2024.[36] The program is an example of successful U.S.-Russian cooperation and Russian specialists have expressed interest in including spent HEU fuel that has accumulated at Russian research reactors into the program. Rosatom is collecting and summarizing the information necessary for decision-making to include spent fuel of the Russian research reactors into the RRRFR program. The spent fuel storage facilities hold about 14,000 fuel assemblies and fuel rods of different types, containing several tons of HEU. About 80 percent of all spent fuel is stored at two sites: The Institute of Physics and Power Engineering (Obninsk) and NIIAR (Dimitrovgrad).[37]

CONCLUSION

By supporting the final communiqués of the Nuclear Security Summits held in Washington, D.C., in 2010 and in Seoul in 2012 and The Hague in 2014, Russia has made clear that it recognizes the urgency of converting research reactors to LEU fuel and minimizing the use of HEU. Given this, it seems advisable for Russia to develop and adopt a national program for the maintenance and development of its fleet of research reactors that promotes progress in the development the nuclear power and defense technologies while meeting its international obligations.

It seems that one aspect of this program would be an audit of all Russian nuclear research facilities. This would make it possible to identify which are no longer necessary and could be shut down because of advanced age and/or lack of use, as well as to inform decisions on the construction of new facilities that can support the experimental infrastructure required to meet the challenges of nuclear power development and comply with modern international standards for nuclear safety and non-proliferation.

Sources of funding for the decommissioning of unnecessary nuclear research installations, the conversion of the research reactors, and the construction of new research facilities must also be identified. The adoption of such a government program would signal to the international community that Russia takes seriously the need to minimize the use of HEU in the civilian sector.

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Name	Owner	Power (MW)	Fuel/Enrichment percent	Commissioning/ Reconstruction	License expiration date	Type of license
IRT*	Moscow Institute of Engi-neering and physics (MEPhI)	2.5	HEU/90	1967/1975	30 June 2009	The application for new license has not been submitted since 30 June 2009
VVR-Ts	Karpov Scientific Research Institute of Physical Chemistry in Obninsk	15	HEU/36	1964 Modern-ization is underway	22 September 2014	Operation
IR-50	Scientific Research and Design Institute of Power Engineering (NIKIET)	0.05	LEU/10	1961	26 November 2014	Operation
TVR	Institute of Theoretical and Experimental Physics (ITEPh)	2.5	HEU/90	1949	20 November 2013	Decommissioning
BR-10	Institute of Physics and Power Engineering (IPPE)	8	HEU/90	1959	27 July 2012	Decommissioning
AM-1	IPPE	10	LEU/10	1954	21 April 2017	Decommissioning
Bars-6	IPPE	6.5 MJ, impulse	HEU/90-96	1994	31 May 2016	Decommissioning
IBR-2 (IBR-2M)	Joint Institute for Nuclear Research (JINR)	2 (average), impulse	PuO_2	1984/2011	9 February 2014	Operation
F-1	Russian Scientific Center "Kurchatov Institute" (KI)	0.024	LEU/2	1946	31 January 2012	Unlicensed since 31 Jan 2012

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Name	Owner	Power (MW)	Fuel/Enrichment percent	Commissioning/ Reconstruction	License expiration date	Type of license
Argus*	KI	0.05	HEU/90	1981	17 July 2014	Operation
IR-8*	KI	8	HEU/90	1957 In 2001 the service life was extended until 2005	20 March 2017	Operation
MR	KI	50	HEU/90	1964	04 February 2016	Decommissioning
GIDRA	KI	0.01 (average) impulse	HEU/90	1972/2003	31 January 2014	Operation
Gamma	RNTs KI	0.125	HEU/90	1982	30 March 2012	The application for license has been submitted
OR*	RNTs KI	0.3	HEU/36	1954/1988	30 June 2013	Operation
Bars-4	Scientific Research Institute for Instruments (NIIP)	4 MJ impulse	HEU/90	1971	13 December 2016	Operation
VVR-M	Petersburg Nuclear Physics Institute in Gatchina	15	HEU/90	1959	31 December 2015	Operation
SM-3	Scientific Research Institute of Atomic Reactors (NIIAR)	100	HEU/90	1992	27 December 2016	Operation
RBT-6	NIIAR	6	HEU/90	1975	31 October 2016	Operation
RBT-10/1	NIIAR	10	HEU/90	1983	31 December 2013	Decommissioning
RBT-10/2	NIIAR	10	HEU/90	1984	30 June 2016	Operation
MIR-M1*	NIIAR	100	HEU/90	1966/1975 Moderniza-tion project has been developed	31 December 2014	Operation
Arbus (ACT-1)	NIIAR	12	HEU/36-90	1963	17 July 2014	Decommissioning

VK-50	NIIAR	220	LEU/3	1965 The service life of the reactor vessel was extended to 2015	25 December 2015	Operation
BOR-60	NIIAR	60	HEU-Pu/90	1969 Life extension work is in progress	31 December 2014	Operation
IVV-2M	Institute of Reactor Materials (IRM)	15	HEU/90	1966/1982	21 October 2015	Operation
U-3	The Krylov Central Research Institute	0.05		1964/1989	24 December 2017	Operation
IRT-T*	Scientific Research Institute of Nuclear Physics at the Tomsk Polytechnic Institute	6	HEU/90	1967/1984	11 November 2015	Operation
PIK	Petersburg Nuclear Physics Institute in Gatchina	100	HEU/90	2011	21 June 2015	Operation
IRV-M1/IRV-M2	NIIP	4	HEU/36	1974–1999	04 February 2016	Construction

Note. *Indicates that the reactor was studied for possible conversion according to the agreement between Rosatom and U.S. Department of Energy