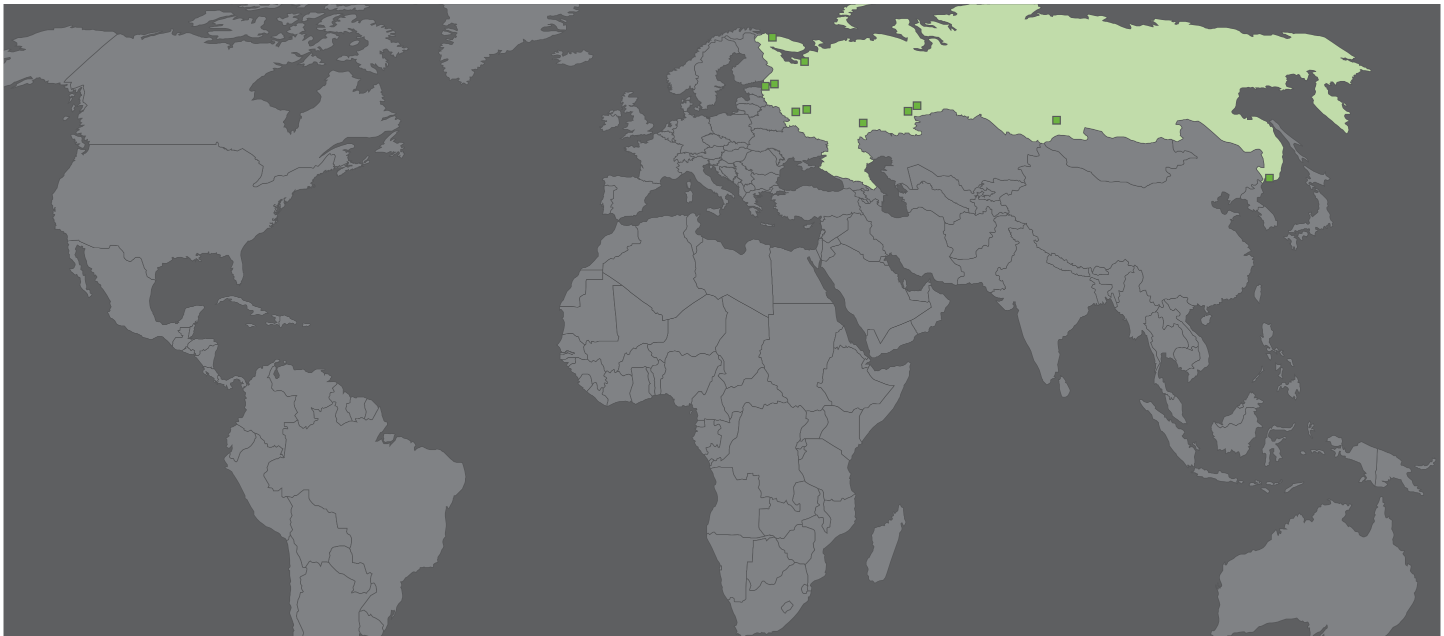

IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

The Use of Highly-Enriched Uranium as Fuel in Russia

Pavel Podvig Editor

Research Report No. 16
International Panel on Fissile Materials

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With contributions by Nikolay Arkhangelskiy, Anatoli Diakov, Anton Khlopkov, Dmitry Konukhov, Dmitry Kovchegin, Eugene Miasnikov

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About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from sixteen countries, including both nuclear weapon and non-nuclear weapon states.

The mission of the IPFM is to analyze the technical bases for practical and achievable policy initiatives to secure, consolidate, and reduce stockpiles of highly enriched uranium and plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear disarmament, halting the proliferation of nuclear weapons, and ensuring that terrorists do not acquire nuclear weapons.

Both military and civilian stocks of fissile materials have to be addressed. The nuclear weapon states still have enough fissile materials in their weapon and naval fuel stockpiles for tens of thousands of nuclear weapons. On the civilian side, enough plutonium has been separated to make a similarly large number of weapons. Highly enriched uranium fuel is used in about one hundred research reactors. The total amount used for this purpose alone is sufficient to make hundreds of Hiroshima-type bombs, a design potentially within the capabilities of terrorist groups.

The Panel is co-chaired by Alexander Glaser and Zia Mian of Princeton University and Tatsujiro Suzuki of Nagasaki University. Its 30 members include nuclear experts from Brazil, Canada, China, France, Germany, India, Iran, Japan, South Korea, Norway, Pakistan, Russia, South Africa, Sweden, the United Kingdom, and the United States. Short biographies of the panel members can be found on the IPFM website, www.fissilematerials.org.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. The reports are available on the IPFM website and through the IPFM blog, www.fissilematerials.org/blog.

Princeton University's Program on Science and Global Security provides administrative and research support for the IPFM. IPFM is supported by grants to Princeton University from the John D. and Catherine T. MacArthur Foundation of Chicago and the Carnegie Corporation of New York.

Summary

Highly-enriched uranium presents a unique challenge from the nuclear security point of view. Because of its nuclear properties, HEU can be used relatively easily in a simple nuclear explosive device; it, therefore, poses significant danger with regard to potential use by non-state actors or states with limited nuclear weapon expertise. Moreover, the material is widely used in a range of non-weapon military and civilian applications, such as naval and research reactors or critical research facilities, which makes it vulnerable to diversion or loss. Substantial amounts of HEU are constantly moving through the fuel cycle, creating constant nuclear security risk. Civilian research facilities, which may lack sufficient protection, are the most problematic, but military uses of HEU also carry with them substantial nuclear security risks.

Understanding of the inherent security risks associated with the continuing use of HEU and of the nuclear proliferation risks associated with these activities helped initiate an international effort, led by the United States and supported by many states, to reduce the use of HEU in civilian applications. Over the last few decades, this effort has made significant progress in removing HEU from research facilities throughout the world and reducing the number of countries that have access to the material. Further progress in HEU minimization will critically depend on the participation of Russia, which currently operates more HEU facilities than the rest of the world combined and is committed to continue to use the material in a wide range of applications.

Russia has never declared the size of its HEU stock, nor has it disclosed detailed information about the facilities that use the material. Independent estimates suggest that it has about 680 tons of HEU, although this number is characterized by a very large uncertainty of about 120 tons.[1] About 160 tons of HEU is probably in assembled nuclear weapons, active as well as those in reserve and awaiting dismantlement. An equivalent of about 25 tons of 90% HEU is believed to be in use in the naval fuel cycle, primarily in the cores of operational naval reactors. Most of the remaining 500 tons of HEU appears to be in the custody of Rosatom and may be stored in bulk form or in weapon components.

As of April 2017, Russia operated 58 facilities that use HEU. This number includes research reactors, critical assemblies, isotope production and power reactors, as well as naval prototypes. This is more than half of the 115 such HEU facilities that are operating globally.[2] In addition, Russia has a fleet of 58 nuclear-powered ships with nuclear reactors that use HEU fuel. Although Russia's nuclear complex has significantly reduced its consumption of HEU in the last two decades, it still requires a large amount of highly-enriched uranium to operate.

As of 2017, it is estimated that Russia uses an equivalent of about 3.3 tons of 90% HEU annually. Most of this material is used in the fuel of naval reactors. These consume about 1.6 tons of 90% HEU each year, which is equivalent to 5 tons of HEU, of various degrees of enrichment.[3] The second largest consumption of HEU is as fuel for breeder reactors. The BN-600 reactor will require about 3.7 tons of HEU annually, which corresponds to about 1 ton of 90% HEU equivalent. The BN-800 reactor uses HEU in its initial core, but it is expected to switch to plutonium fuel. Tritium production reactors account for significant HEU demand as well. As of 2017, with one of the two reactors shut down for modernization, tritium and other industrial isotopes production requires about 0.5 tons of 90% HEU. Starting in 2018, when the second reactor is expected to return to service, the total consumption will increase to 1.1 tons of 90% HEU (increasing the total annual HEU demand to about 3.9 tons of 90% HEU). Russian research reactors are estimated to consume about 0.23 tons of 90% HEU annually.

In addition to the new material that is required to manufacture new fuel, there are significant amounts of HEU associated with various research facilities, such as pulsed reactors or critical assemblies. It is estimated that as of 2017, about 9 tons of HEU (6 tons of 90% HEU equivalent) was associated with 38 research facilities in ten organizations throughout Russia (see Chapter 2).

As these numbers indicate, HEU minimization efforts in Russia will face considerable challenges, as they will have to deal with a variety of applications and large amounts of material involved. This report undertook an effort to conduct a systematic analysis of non-weapon uses of HEU in Russia and previous HEU minimization programs in order to better understand the challenges of reducing the use of HEU and identify approaches that may help address these challenges.

One of the key conclusions of this report is that significant progress in HEU minimization in Russia would be extremely difficult without a comprehensive international strategy for dealing with all aspects of HEU use. A program that is narrowly focused on civilian research reactors would not make a visible contribution to reducing the risks associated with the use of HEU in Russia. More importantly, a narrow program is unlikely to gain the support of key internal constituencies in Russia, such as its nuclear complex's technical community.

Given the variety of applications that use HEU in Russia and the range of enrichments involved, an effective comprehensive HEU minimization strategy should include a consistent approach to the use of HEU in high-performance civilian reactors, in defense-related research facilities, as well as in naval reactors. A clear policy on the use of HEU with medium enrichments would be important as well. Eventually, this strategy should also address the nuclear security risks associated with weapon-related uses of HEU. Russia is unlikely to support a comprehensive minimization program unless it is developed in a multinational context with substantial input from Russian technical experts.

It is also important to note that Russia has already made significant progress in reducing the number of HEU research facilities and successfully participated in international HEU minimization efforts, such as the return of Soviet-origin fuel from abroad or development of advanced LEU fuels. Internally, Russia has all necessary elements of the scientific, technical, and organizational infrastructure that can support an ambitious HEU minimization program. Despite the political setbacks of the last few years, Russia's technical community is open to cooperation and could make a substantial contribution to the global effort to reduce the use of highly-enriched uranium.

The report is structured in the following way: The introductory chapter, written by Pavel Podvig, presents a brief overview of the reactor use of HEU in Russia and outlines the history of Russia's involvement in cooperative HEU minimization programs. The second chapter, also authored by Pavel Podvig, describes the use of HEU in pulsed reactors and critical assemblies. The following chapter, written by Anatoli Diakov, provides an overview of the efforts to convert civilian research reactors to LEU fuel. In Chapter 4, Nikolay Arkhangelskiy describes the origins and the key achievements of the program to convert Soviet-origin reactors abroad. The associated effort to transfer fresh and spent fuel of Soviet-origin research reactor to Russia is detailed by Anton Khlopkov and Dmitry Konukhov in Chapter 5 of the report. Chapter 6, authored by Dmitry Kovchegin, describes the key elements of Russia's nuclear security structure that apply to HEU use in civilian research facilities. Chapter 7 of the report deals with the Soviet and Russian naval reactor program. Eugene Miasnikov is the primary author of this chapter, with Pavel Podvig contributing the section on estimated HEU consumption in naval reactors.[4] The concluding chapter of the report is written by Pavel Podvig. He also prepared the appendices, which contain a list of all Russian HEU facilities, a list of all Soviet-origin reactors outside of Russia, and a summary table of removals of HEU fresh and spent fuel from Soviet-origin reactors. Pavel Podvig prepared all charts in the report, including those that appear in chapters authored by other contributors.

It should be noted that while the conclusions of the report are based on individual contributions, these conclusions do not necessarily reflect the opinions of all authors. The authors are only responsible for their direct contributions. As the project leader and the editor of the report, Pavel Podvig, is responsible for the conclusions as well as for all errors and inaccuracies in the text.

The project has benefited from the efforts of two working meetings. The first workshop, "International cooperation in minimizing the use of HEU in research", held at the IAEA's headquarters in Vienna on September 25–26, 2013, discussed the experiences of various international HEU minimization projects. The meeting was organized in close cooperation with the Research Reactor Section of the IAEA's Division of Nuclear Fuel Cycle and Waste Technology. The workshop held in Moscow on June 17, 2014, brought together Russian experts who contributed to the report.

This project was generously supported by the MacArthur Foundation. Princeton University's Program on Science and Global Security provided invaluable assistance at all stages of the project. Last, but not least, the project would have been impossible without the support of Pablo Adelfang, Alexander Glaser, Zia Mian, and Frank von Hippel, as well as participants of the two workshops, who shared their knowledge and experience and invested considerable time into the project.

1 INTRODUCTION
Reactor use of highly enriched uranium in Russia

History of reactor use of HEU in Russia

Highly-enriched uranium offers a number of significant advantages when used as fuel in nuclear reactors. Most of these advantages result from the fact that an increased concentration of the fissile isotope uranium-235 makes it easier to build reactors with a high neutron output or a high neutron flux, which are useful in research or isotope production applications. In naval reactors, the use of HEU facilitates longer service life of a reactor core and may help achieve better reactor performance. Since, until recently, the availability or cost of HEU was rarely a significant constraint, most applications moved toward using uranium with higher enrichments whenever it was practical.

In looking at the history of HEU use in the Soviet Union and Russia, it is important to understand that research reactors account for a very small share of HEU consumption. HEU was first used in nuclear weapons, but then its use was broadened to a large number of applications, military as well as civilian.[5] The history of HEU consumption in the Soviet Union and Russia is shown on Figure 1.1. Figure 1.2 shows estimated projected annual consumption of HEU in the next decade.

The first Soviet reactor that used enriched uranium in fuel was the AI-IR production reactor, built at what is now the Mayak Plant to produce tritium for the nuclear weapon program. The reactor began operations in December 1951 using fuel with uranium enriched to 2% in uranium-235. Later it started using 10% low-enriched uranium (LEU) fuel and was converted to use 80% HEU in 1967 and 90% HEU in 1969.[6] Around that time other production reactors started using highly-enriched uranium (HEU) fuel as well.[7] The graphite plutonium production reactors gradually introduced 90% HEU fuel in some of their fuel channels during 1966–1967.[8] As a result, Soviet production reactors became significant users of HEU, using in total upwards of 300 kg of 90% HEU annually. Most Russian plutonium production reactors were shut down during 1989–1990, but three continued to operate until 2008–2010.

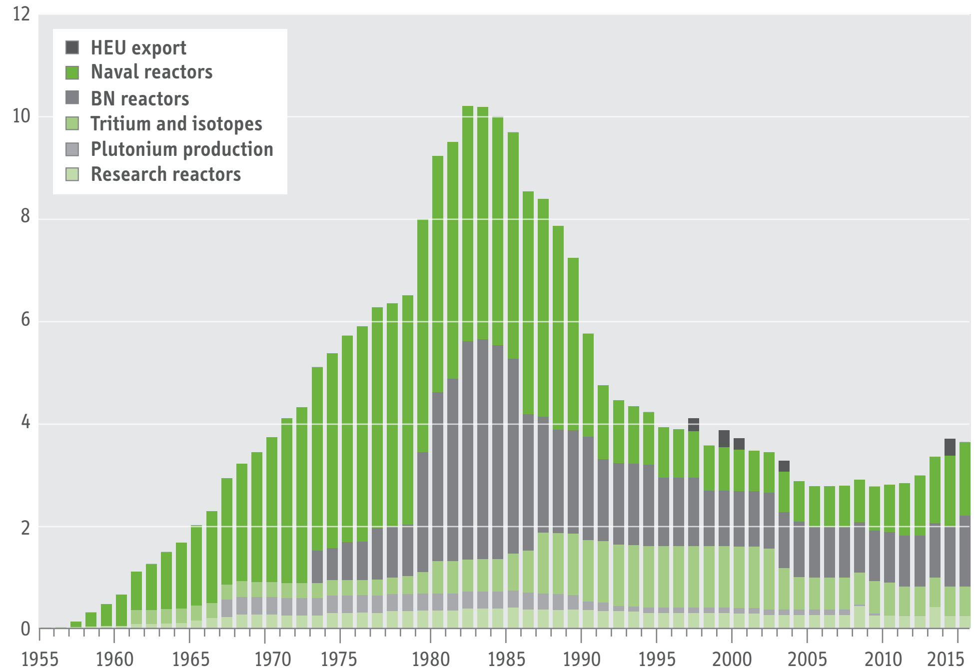

Figure 1.1. Estimated amount of highly-enriched uranium (in tons/year 90% HEU equivalent) consumed by various programs.

The production of tritium in early heavy-water reactors, which started to use HEU in 1961, consumed roughly 300 kg of 90% HEU a year. This amount more than doubled in early 1980, when the Mayak plant started operating a 1000-MWt light-water tritium production reactor, *Ruslan*. Following the startup of the LF-2 heavy-water reactor for tritium production, which replaced the old OK-190M in 1988, the amount of HEU consumed increased even further.[9] With two reactors operating, tritium production consumed an estimated 1100 kg of 90% HEU a year. In the 1990s, *Ruslan* and LF-2 underwent an upgrade that allowed them to produce a range of industrial isotopes (e.g. cobalt-60).[10] Although they are capable of producing tritium if necessary, civilian radio-isotope production became the reactors' primary mission.[11] The reactors are undergoing another round of modernization—in 2011 LF-2 completed an overhaul that started in 2004.[12] *Ruslan* was shut down for extensive modernization in 2011, but it is expected to return to operations in 2018.[13] Mayak plans to replace *Ruslan* and LF-2 with a new multipurpose reactor that is expected to come online in 2023.[14] It is not known if the new reactor will use HEU fuel.

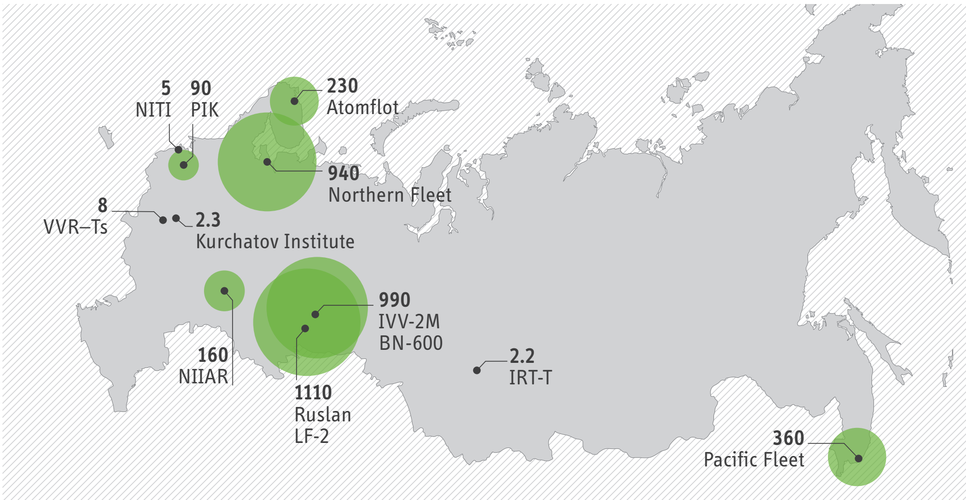

Figure 1.2. Projected annual consumption of HEU (kg of 90% HEU equivalent a year) by operational reactors in Russia that use HEU fuel after 2017.

Starting in the late 1950s, the naval reactor program also started to consume substantial amounts of HEU, although most submarine reactors used uranium with enrichments of 21–45% (see Chapter 7). By the end of the 1980s, the Soviet Union had built more than 200 nuclear submarines; virtually all of them remained in service at the time. The annual consumption of HEU in naval reactors grew steadily from 1958 to a peak of about 4.5 tons of 90% HEU equivalent by 1990. Cumulatively, by the end of 2015, naval reactors (civilian as well as military) had consumed about 155 tons of 90% HEU equivalent in the form of 610 tons of HEU with enrichments of 21% to 90% (see Chapter 7).

The precipitous decline in the number of operational submarines after 1990 probably decreased their combined HEU requirements to about 1 ton of 90% HEU equivalent per year. Taking into account new submarine construction results in a projected annual consumption of HEU in naval reactors in the next decade of about 1.4 tons of 90% HEU equivalent (see Chapter 7). Of this amount about 0.19 tons/year will be consumed by civilian transport reactors and about 1.25 tons/year by submarines.

Finally, with the launch of the first fast-neutron power reactors, BN-350 in 1973 and BN-600 in 1981, power generation became another large consumer of HEU. While these reactors used uranium with an enrichment no higher than 33%, the quantity of material used was very large. Before being permanently shut down in 1998, the BN-350, deployed in Kazakhstan, consumed 22 tons of 21% HEU and 54 tons of 26% HEU (plus 36 tons of 17% LEU). This corresponds to an average annual HEU consumption of about 3 tons of HEU (0.8 tons of 90% HEU equivalent). The BN-600, in addition to 17% LEU, requires on average 3.7 tons of HEU annually (1.5 tons of 21% HEU, 2.2 tons of 26% HEU) corresponding to an annual consumption of about 980 kg of 90% HEU equivalent. About a third of the initial core of the new fast reactor, the BN-800, which went critical in June 2014, is HEU fueled. However, the reactor is expected to switch to plutonium-based fuel after the initial load.[15]

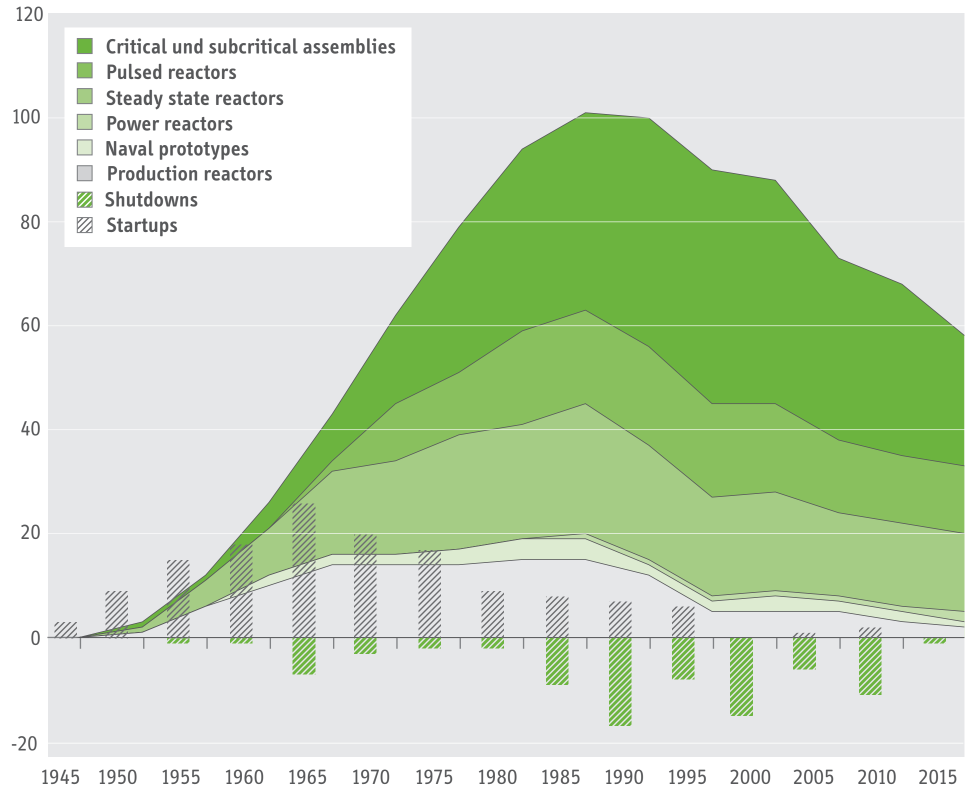

Figure 1.3. Number of HEU-fueled facilities in Russia. Naval reactors and facilities in former Soviet states are not included.

The first research reactors in Russia that used enriched uranium in their fuel were built in the 1950s. Initially they used fuel with 10% LEU, but starting around 1957–1958, most were converted to HEU fuel enriched to 36% or 90% in uranium-235. The number of research reactors with HEU grew steadily until about 1990, with more than ten new facilities becoming operational every five years (see Figure 1.3; the list of reactors and research facilities that used HEU is given in Appendix A). Very few reactors or research facilities were shut down before 1990 and most of those were replaced by more capable new facilities. Compared to its peak in the 1980s, the total consumption of HEU has been significantly reduced, although the general structure of the HEU use remains largely intact. Research facilities account for a relatively small share of the overall HEU consumption. The largest research reactors, such as SM-3 in Dimitrovgrad, require less than 100 kg of 90% HEU a year to operate. In total, the steady state research reactors that operated in 2017 consumed about 290 kg of HEU, virtually all 90% enriched.

Substantial amounts of HEU also are used in numerous critical assemblies and pulsed reactors, which have lifetime cores. For example, the two BFS critical assemblies at the Institute of Physics and Power Engineering in Obninsk have about 4 tons of HEU (about 2 tons of 90% HEU) associated with them. The total amount of HEU contained in critical facilities and in pulsed reactors that were believed to be operational in 2016 is estimated to be about 9 tons (6 tons 90% HEU equivalent).

The key factors that led to the reduced use of HEU in Russian reactors were the decommissioning of a large number of nuclear submarines and the shutdown of most plutonium production reactors after the end of the Cold War. Also, in the 1990s Russia began the process of shutting down and decommissioning a number of research reactors and critical assemblies. At the early stages, this process was largely driven by operators of the facilities, in response to specific economic and social circumstances they had to deal with. Usually, the most pressing concern was radioactive cleanup, especially at sites located in urban areas, such as Moscow. By 2008 most of the activities related to the decommissioning of nuclear facilities, which included plutonium production reactors and radioactive waste storage sites as well as research installations, were included in the first Federal Targeted Program "Nuclear and Radiation Safety in 2008 and through 2015."[16] Rather than setting its own goals regarding minimization of HEU use or, indeed, the optimization of the structure of research facilities, this program largely consolidated funding and programmatic support for the activities that were already underway. Nevertheless, it became an extremely important tool for addressing a range of issues related to removal of radioactive material and, in some cases, HEU from a number of sites.

The leading role in the effort to secure the sites and reduce the amount of HEU in circulation belongs to a range of international cooperation and assistance programs that Russia engaged in starting in the 1990s. These programs, described in the following section, significantly improved security at virtually all sites, eliminated large quantities of HEU and built a good foundation for a continuing HEU minimization effort.

HEU minimization programs

International cooperation and technical assistance played a very important role in the worldwide proliferation of research facilities using HEU. International cooperation also has been key to the effort to roll back the use of HEU in civilian applications worldwide and in helping Russia to improve security at its civilian and military facilities that handle fissile materials. Russia has moved to disengage from most international programs in this area in the past two years, however, and, although some coordination of activities is likely to continue, maintaining Russia's active involvement in the effort to minimize the use of HEU will require development of new approaches to international cooperation in the area of nuclear security. This section provides a brief overview of the history of past international cooperation in the area of nuclear security and HEU minimization and considers some suggestions for how to take this cooperation forward.

In the 1950s, the Soviet Union launched its own version of the U.S. "Atoms for Peace" program, which provided research reactors and other nuclear research facilities to its friends and allies. When the nuclear test conducted by India in 1974 brought attention to the potential nuclear proliferation implications of this assistance, the Soviet Union became involved in the process that led to reevaluation of the internationally accepted practices in this area. During 1977–1980, it participated in the International Nuclear Fuel Cycle Evaluation (INFCE) forum that, for the first time, systematically addressed the nuclear proliferation risks associated with nuclear reactors and their fuel cycles. Among other recommendations, the study urged minimization of the use of HEU in civilian research reactors.

Another important development at the time was the launch in 1978 of the Reduced Enrichment for Research and Test Reactors (RERTR) program in the United States. As discussed in Chapter 4 of this report, even though the Soviet Union was not directly involved, the RERTR program was the key factor that led the leadership of the Soviet nuclear complex to launch its own effort to reduce enrichment in Soviet-origin research reactors abroad. This initiative reflected the views of technical community, which were informed by the international discussion of the issue through the contacts that the Soviet scientists had with their colleagues abroad. Although the Soviet program did not result in actual reactor conversions, it did represent a significant policy change. It also prepared ground for the subsequent work on conversion of Soviet-origin reactors outside Russia.

In the immediate aftermath of the breakup of the Soviet Union, the security of all nuclear materials in the Russian nuclear complex, military as well as civilian, became the focus of a range of cooperative programs. Initial efforts were concentrated on securing Russia's nuclear warheads and military fissile materials. Later cooperation and assistance efforts included termination of the production of weapon-grade plutonium and the elimination of excess fissile materials, assistance with downsizing the Russian nuclear complex, security at civilian sites, repatriation to Russia of Soviet and Russian-origin fresh and spent HEU fuel, consolidation of fissile materials, and conversion of research reactors abroad and in Russia.

Physical security of nuclear warheads was one of the goals of the U.S. Cooperative Threat Reduction (CTR) program (often referred to as the Nunn-Lugar program) that was established in 1991 to provide assistance to Russia in the dismantlement of its excess weapons of mass destruction. The program, managed by the U.S. Department of Defense (DoD), included a number of projects at Russian nuclear weapon storage and handling sites. DoD provided security at centralized warhead storage facilities as well as smaller storage sites in the Russian Rocket Forces, Navy, and Air Force bases. It also worked on improving security of warheads in transit.[17] The actual assistance was provided by the Department of Energy's (DOE's) Sandia National Laboratory.

In 1993, DOE launched the International Materials Protection and Cooperation program. This program provided assistance in securing facilities that handled naval fuel and providing physical security upgrades at the facilities managed by the Ministry of Atomic Energy (now Rosatom).[18] Initially, the DoD and DoE programs assisted Russia with providing security upgrades for more than 200 buildings. At the summit meeting in Bratislava in 2005, the scope of the program was expanded to include additional military and Rosatom sites. In 2008, all upgrades at the 97 Russian military sites included in the extended scope were completed.[19] The Department of Energy continued its work on security upgrades at Rosatom sites up until the end of 2014. At that point, upgrades were completed in all but eight buildings.[20]

Three major U.S.-Russian projects initiated in the 1990s were designed to stop production and irreversibly eliminate weapon-origin fissile materials:

- The HEU-LEU or Megatons to Megawatts deal reduced by 500 tons the quantity of excess weapons HEU in Russia and strengthened the security at Rosatom sites.
- The 1997 Plutonium Production Reactor Agreement provided Russia with assistance in shutting down its plutonium-production reactors.[21]
- The 2000 Plutonium Management and Disposition Agreement (PMDA) was a preliminary understanding regarding the verifiable elimination of 34 tons of weapon-grade plutonium by each country. The PMDA was amended in 2010.[22]

The HEU-LEU deal was one of the most successful U.S.-Russian cooperation programs.[23] The first shipments of material took place in 1996 and the program was completed at the end of 2013.[24] It has been estimated that as a result of the deal Russia received about $17 billion in payments for the embedded enrichment work and natural uranium feed contained in the blended down LEU that it supplied to the United States.[25] The HEU-LEU program provided essential support to the Russian nuclear industry and contributed to better security of the materials in its enterprises. It has made a significant contribution toward reducing the global stocks of HEU and has provided a model for transparency in the elimination of nuclear materials released by the dismantlement of weapons.[26]

Russia's excess civilian HEU was addressed by a different program, DoE's Material Conversion and Consolidation project, which paid to down-blend excess civilian HEU.[27] This resulted in the down-blending of 16.8 tons of HEU as of the end of 2014.[28] DoE identified additional 5.2 tons of HEU eligible for downblending.[29]

A very important U.S.-Russian cooperative program launched in the 1990s was the Russian Research Reactor Fuel Return (RRRFR) program, described in detail in Chapter 5 of this report. The program provided a framework for systematically addressing the return to Russia of fresh and spent HEU fuel from Soviet-origin reactors.

In 2004, the United States established a new program, the Global Threat Reduction Initiative (GTRI), which consolidated a range of projects dealing with the threats associated with the civilian use of HEU and radioactive materials. Initially, GTRI included the RRRFR, the U.S.-origin research reactor fuel acceptance program and the RERTR program, as well as a range of other activities.[30] GTRI became the primary vehicle for the U.S.-led international effort to reduce and protect vulnerable nuclear materials at civilian sites and provided effective support for a range of U.S.-Russian cooperative nuclear security and HEU minimization programs. In 2015, GTRI was folded into the new Material Management and Minimization (M^3) program, which includes Conversion, Nuclear Material Removal, and Material Disposition subprograms.[31]

An important expansion of U.S.-Russian cooperation in the area of nuclear security was the Bratislava Initiative, which was announced by the presidents of the United States and Russia at a summit meeting in February 2005.[32] As part of the initiative, the two countries agreed on a list of Russian nuclear facilities that required security upgrades and made a commitment to work together on a number of other nuclear security projects. In particular, the United States and Russia agreed to expand their joint work on the development of LEU fuels for reactors in third countries. To coordinate the work, the presidents established a bilateral Senior Interagency Working Group, co-chaired by the U.S. Secretary of Energy and the head of Russia's Rosatom.

This new structure proved instrumental in achieving an agreement on expanding the scope of the reactor conversion work into Russia. In 2010, the United States and Russia agreed to conduct feasibility studies of the conversion of six HEU-fueled research reactors in Russia and established a working group to coordinate this activity.[33] The agreement also included cost-sharing provisions, with the United States covering the cost of fuel development and qualification and Russia supporting fuel fabrication.[34] The studies of the six research reactors, completed in 2013, confirmed the technical feasibility of converting them to LEU and identified directions for further work.[35] The first reactor was converted in 2014 (see Chapter 3).

The high-level political support of the nuclear security programs in Russia and the organizational framework provided by the senior-level working group established in Bratislava created conditions for an expansion of the work into additional areas. Specifically, the United States and Russia were planning to continue their work on the development of advanced LEU fuels for research reactors, to expand the scope of reactor conversion feasibility studies beyond the initial list of six reactors, and to support consolidation of fresh and spent HEU fuel from Russian converted and decommissioned research reactors.[36] The United States and Russia signed an agreement on cooperation in scientific research and development that was intended to stimulate additional joint projects.[37] The political developments in 2014 dramatically down-sized the scope of U.S.-Russian cooperation, however, resulting in termination of most bilateral programs.

The change in the scale of the nuclear security cooperation efforts was precipitated by the general crisis in U.S.-Russian relations caused by the events in Ukraine in the spring and summer of 2014. It also reflected, however, a gradual evolution of Russian Government attitudes toward cooperation that has been underway for more than a decade. In the model established in the early 1990s, Russia was a recipient of assistance, rather than an equal partner. Even though some projects involved a more equitable sharing of responsibilities, Russia was not content with the general framework of the cooperation programs.

In the most visible sign of its intention to move away from the old framework, Russia made a decision not to extend the 1992 U.S.-Russian agreement that provided a legal foundation for the U.S. Cooperative Threat Reduction program activities and that was subsequently used in all U.S. assistance projects in Russia.[38] The taxes and liabilities exemptions in the document usually referred to as the CTR umbrella agreement are widely believed by both U.S. and Russian observers to be unfavorable to Russia. Although the Russian government extended the agreement without significant modifications twice, in 1999 and 2006, it was allowed to expire in 2013.[39]

The CTR umbrella agreement was replaced by a different arrangement much more limited in scope, a bilateral protocol to the 2003 Framework Agreement on a Multilateral Nuclear Environmental Programme in the Russian Federation (MNEPR).[40] The MNEPR agreement originally provided a legal basis for assistance programs that were implemented by the members of the Global Partnership Against the Spread of Weapons and Materials of Mass Destruction established at the G8 summit in Kananaskis in 2002.[41] These programs primarily covered environmental cleanup and assistance with the dismantlement of decommissioned submarines. The United States joined the MNEPR agreement in 2003, but did not sign its liabilities protocol as it relied on the CTR liability arrangements instead.

The U.S.-Russian bilateral protocol to MNEPR, signed in 2013, covered cooperation on a broad range of issues that included physical protection, control and accounting, consolidation of nuclear material and downblending, conversion of Russian HEU-fueled research reactors and development of new LEU fuel, as well as work on submarine decommissioning. The key provisions of the protocol were based on the liability arrangements that were developed for the U.S.-Russian Plutonium Management and Disposition agreement. On the Russian side, Rosatom and Rostekhnadzor were named among the executive agents responsible for implementation of the restructured cooperation programs. The Russian ministry of defense did not participate in the new arrangement.

Although the MNEPR program allowed most U.S.-Russian joint projects to continue, the Russian political leadership had apparently already made a decision to curtail most nuclear security cooperation projects. Rosatom reportedly told the United States that it would be reducing its participation in those programs as early as November 2013.[42] Rosatom officials have indicated that the decision to end all assistance projects by the end of 2014 was made in 2013, long before the Ukraine crisis.[43]

Russia formally informed the United States about its decision to end the cooperative programs at a meeting of the nuclear security working group in December 2014 in Moscow. Russia had already decided in October 2014 against launching new projects, while allowing the projects already underway to continue.[44] The United States reportedly informed Russia about its intent to scale down cooperation as early as April 2014, but formally made the decision in December 2014.[45]

Among the programs suspended as a result of the 2014 decisions were the Russian reactor conversion program, development of advanced LEU fuels, downblending of non-weapon HEU (the Material Conversion and Consolidation project), and nuclear security cooperation work that involved most Rosatom sites (in particular, physical security upgrades at eight buildings at Mayak). Russia expressed its interest in continuing the cooperation on repatriation of Russian-origin HEU fuel from third countries. Some work in Russia with non-Rosatom organizations, such as Kurchatov Institute or Rostekhnadzor, will continue, but Rosatom officials indicated that these projects will end in 2015.[46]

Russian officials have cited several factors as justifying the decision to curtail the cooperation programs. Most importantly, they argued that most of the nuclear security work has already been done and that Russia is planning to complete the unfinished projects without outside assistance. Rosatom has publicly expressed its commitment to continue the work on a number of projects, such as reactor conversion, and to do it in cooperation with the United States.[47] However, Rosatom officials admitted that conversion of research reactors from HEU to LEU fuel is not a high-priority area. There are differences in priorities in other areas as well. According to Rosatom, it put forward a number of proposals to its U.S. counterparts, but those were not picked up. In some cases, Rosatom believed that the scope of the DoE projects was too narrow, making it difficult to address problems in a systematic way. The uncertainties of the U.S. funding cycle were also cited as one of the factors impeding productive work.[48]

Thus, the prospects for renewing U.S.-Russian cooperation in the nuclear security area are not clear. According to the U.S. Department of Energy's Congressional Budget Request for fiscal year 2016, the Material Minimization and Management program "will continue to look for partnership opportunities with Russia, on the general assumption that each side shall independently bear its costs related to cooperative activities".[49] The Conversion subprogram was planning to continue its work on reactor conversion in Russia, albeit on a limited scale. Its role in converting additional reactors in Russia was "anticipated to be limited to only technical exchanges."[50]

It appears that Rosatom would not object to maintaining a certain level of cooperation with the United States. However, the decision to curtail the joint projects appears to have been made by Russia's political leadership. In October 2016, Russia formally suspended the U.S.-Russian agreement on cooperation in nuclear- and energy-related research that provided the basis for all reactor conversion work.[51] Russia also suspended implementation of the Plutonium Management and Disposition Agreement.[52]

Despite the recent setbacks, U.S.- Russian cooperative efforts have made outstanding progress in strengthening physical security at Russian nuclear facilities, eliminating weapon-origin nuclear material, removing HEU and shutting down or converting research reactors in third countries. Also, the close contacts between U.S. and Russian scientists and technical experts, developed in the process, will help sustain interest in cooperation despite political downturns. At the same time, in the area of HEU minimization, it is unlikely that U.S.-Russian cooperation will be the primary driver of future efforts in that area, certainly not to the extent it has been in the past. Russia has long been seeking to redefine international cooperation on the basis of equal partnership and to focus more on multinational nuclear security efforts and those done under the aegis of the IAEA in particular. In the future, Russia is likely to insist on its own nuclear security agenda, which does not seem to place HEU minimization high on the list of priorities. It will continue to support some HEU minimization projects, such as repatriation of HEU fuel and conversion of reactors in third countries. Should the political environment become more favorable for the resumption of U.S.-Russian technical cooperation, Russia may work with the United States on the development of advanced LEU fuels for research reactors and even on conversion of some reactors in Russia. It is difficult to imagine, however, circumstances in which U.S.-Russian cooperation alone would be a strong enough factor to convince Russia to initiate a comprehensive HEU minimization effort.

2 Pulsed reactors, critical and subcritical assemblies

Introduction

Pulsed reactors and critical assemblies are major non-consumptive users of highly-enriched uranium. As in other research applications, HEU offers a number of advantages. In pulsed reactors, it facilitates achieving high fast neutron flux. Critical assemblies built to model and validate active zones of HEU-fueled research and power reactors must also use HEU fuel.

In Russia, these facilities account for most of the HEU stock in research facilities. The amount of the material in pulsed reactors and critical and subcritical assemblies is estimated to be about 9 tonnes (approximately 6 tonnes 90% HEU equivalent). This material is used in 38 research facilities across ten organizations (see Table 2.1). The number of facilities that have an operating license is smaller, since some assemblies are part of a larger facility and operate under its license. These assemblies are listed separately in the table if they have a distinct set of fuel elements associated with them.

From a nuclear security point of view, the fuel in pulsed reactors and critical assemblies is of particular concern since it contains low concentrations of fission products and therefore is not self-protecting like the fuel in the cores of steady-state research reactors. Also, critical assemblies and pulsed reactors can contain tens or hundreds of kilograms of weapon-grade HEU (see Table 2.1). In the case of two critical assemblies operated by the FEI institute in Obninsk, BFS-1 and BFS-2, the HEU stock associated with them is estimated to be about 4 tonnes of HEU (about 2 tonnes of 90% HEU equivalent). A significant fraction of the BFS fuel is in the form of metal. HEU-molybdenum alloy fuel is also used in most pulsed reactors. In this form the material is directly weapons usable.

Over the years, the Soviet Union built a large number of critical assemblies and pulsed reactors that were used in a wide range of military and civilian applications. The first critical facility, FKBN, was built in 1949 for the Soviet nuclear weapons program, in what is now VNIIEF in Sarov. After several modernizations and upgrades, it still operates in Sarov as FKBN-2M.

In the early 1990s, there were 45 known HEU critical and subcritical facilities in Russia. By 2017 that number had been reduced to 25, most of them at two institutions—the Kurchatov Institute in Moscow and the FEI institute in Obninsk.

The number of operational pulsed reactors also reached its peak in the early 1990s when there were 19, most of them at the two nuclear weapon laboratories—VNIIEF in Sarov and VNIITF in Snezhinsk. By 2017 this number was down to 13, with 10 in VNIIEF and VNIITF.

Facility	Type	Enrichment (%)	HEU (kg)
National Research Centre Kurchatov Institute, Moscow			
Gidra	PR, space	90	3.2
Aksamit	CA, space	90	210
RP-50	CA, space	90	~100
Narciss-M2	CA, space	96	27
Filin	CA, space	90	~10
Chaika	CA, space	90	~10
Astra	CA, HTGR	21	120
Delta	CA, naval reactors	80, 90	~100
Kvant	CA, naval reactors	90	~100
Efir-2M	CA, Ruslan reactor	90	~100
All-Russian Scientific Research Institute of Experimental Physics (VNIIEF), Sarov			
BIGR	PR, irradiation, lasers	90	440
BR-1M	PR, irradiation	90	160
BR-K1	PR, irradiation	36	1400
GIR-2	PR, irradiation	90	162
FKBN-2M	CA, critical systems	90	~300
VIR-2M	PR, irradiation, lasers	90	8.7
IKAR-S	CA, IKAR-500 reactor, lasers	90	24
All-Russian Scientific Research Institute of Technical Physics (VNIITF), Snezhinsk			
IGRIK	PR, irradiation	90	6
YAGUAR	PR, irradiation	90	18
BARS-5	PR, irradiation, lasers	90	290
RUN-2	SCA, lasers	90	50
EBR-L	PR, lasers	90	72
RUS-V	PR, irradiation	90	100
FKBN-2	CA, critical systems	90	272
Institute of Physics and Power Engineering (FEI), Obninsk			
BFS-1 and BFS-2	CA, fast reactors	90 36	700 3000
FS-1M	CA, irradiation	90	250
BARS-6	PR, irradiation, lasers	90	220
OKUYAN	SCA, lasers	90	1.2
K-1	CA, space reactors	90	~50
Research Institute of Atomic Reactors (NIIAR), Dimitrovgrad			
FM MIR.M1	CA, MIR.M1 reactor	90	20
FM SM-3	CA, SM-3 reactor	90	40
Institute of Theoretical and Experimental Physics (ITEF), Moscow			
MAKET	CA, LF-2 reactor	90	~100

Scientific Research Institute for Instruments (NIIP), Lytkarino			
BARS-4	PR, irradiation	90	220
Petersburg Nuclear Physics Institute, Gatchina			
FM PIK	CA, PIK reactor	90	30
Central Physical-Technical Institute of the Ministry of Defense (TsFTI MO), Sergiyev Posad			
Priz	PR, irradiation	90	50
Experimental Design Bureau of Machine-Building (OKBM), Nizhniy Novgorod			
ST-659	CA, naval reactors	21–45	~100
ST-1125	CA, naval reactors	21–45	~100
Bauman Moscow State Technical University (Bauman MGTU) and Scientific Research and Design Institute of Power Engineering (NIKIET), Moscow			
FS-2	SCA, training	36.7	2.9

Table 2.1. HEU-fueled pulsed reactors (PR), critical assemblies (CA), and subcritical assemblies (SCA).

Unlike steady-state research reactors, critical assemblies and pulsed reactors are rarely converted to LEU (with the exception of critical assemblies that are used to model reactors that are converted). The reduction of the number of operating facilities of this kind was primarily a result of shutting down old and redundant facilities and occurred mostly during the 1990s and early 2000s. The remaining facilities are used in a range of research and development programs and most are likely to continue to operate. The following sections describe the key areas of research and the prospects for further reductions. Appendix 2A contains a detailed description of organizations and the research facilities that they operate or have operated in the past.

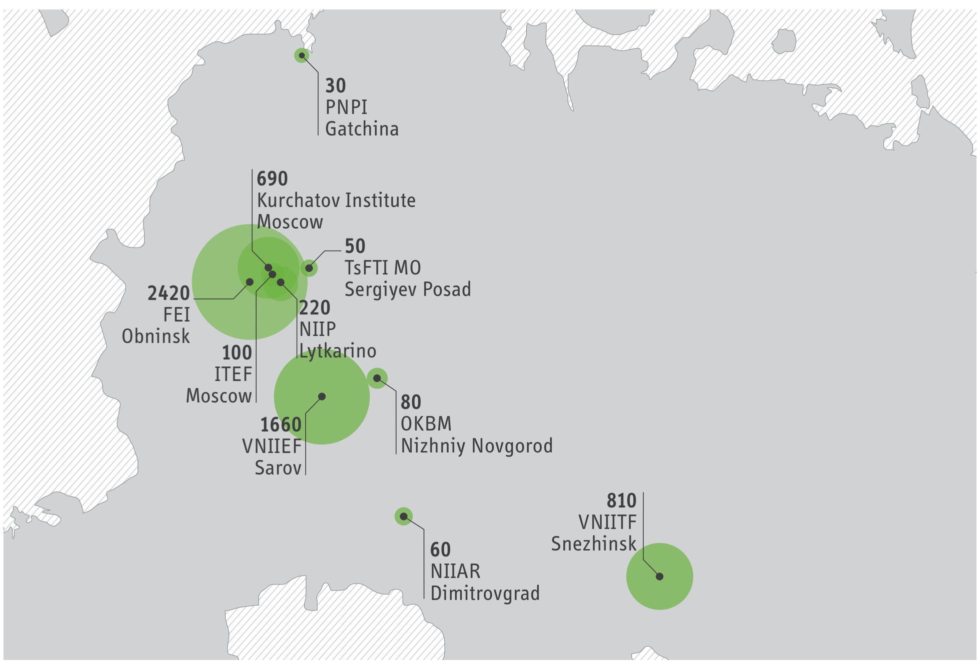

Figure 2.1. Amounts of HEU (kg of 90% HEU equivalent) in operational pulsed reactors, critical and subcritical assemblies.

Research and development programs

New reactor research and development

One of the applications that uses critical facilities extensively in Russia is the development of new nuclear reactors. The two critical assemblies that contain the largest amount of HEU—BFS-1 and BFS-2 in Obninsk—provide the capability to build full-scale models of various reactor cores and are used to support the Russia's fast-neutron plutonium breeder reactor development program. Since the fast neutron reactors built in the Soviet Union, the BN-350 and BN-600, use HEU fuel of various enrichment, the critical facilities possess large amounts of HEU.

It has been suggested that BFS-2 could eliminate its stock of HEU with an enrichment higher than 36%. However, the current BFS program of experiments would require keeping as much as 1.5 tonnes of 36% HEU as well as a significant amount of HEU with an enrichment of 20–22% uranium-235.[53] This means that full conversion of the BFS facilities is unlikely. The transition to plutonium-based fuel in the new fast-neutron reactors, such as the BN-800, may help reduce the HEU stock at the BFS assemblies.[54] However, this would replace one weapon-usable material with another, yielding no significant nuclear security benefits.

Another reactor-design project that involves an HEU critical facility is the work on high-temperature gas-cooled nuclear reactors. The Astra critical facility at the Kurchatov Institute is participating in a number of international projects that explore configurations of active zones of pebble-bed reactors.[55] One of these projects, the Gas-Turbine Modular Helium Reactor (GT-MHR), is partially supported by the United States as part of the 2010 U.S.-Russian Plutonium Management and Disposition Agreement.[56] The Astra facility is currently undergoing reconstruction, so it is expected to continue operations. Since its fuel elements contain uranium with 21% uranium-235, barely above the HEU-LEU dividing line, conversion may not be a high-priority goal.

Physical models of existing reactors

Three critical assemblies are used to model the cores of operational research reactors. These are the FM MIR.M1 and FM SM-3 facilities in Dimitrovgrad, and the FM PIK critical assembly in Gatchina. The conversion of these facilities is closely linked to the conversion of the associated research reactors. MIR.M1 has been considered for conversion, but no specific plans have been made yet (see Chapter 3).

Two critical assemblies are used to optimize the configurations of the cores of the tritium-production reactors that operate at the Mayak plant in Ozersk. Ephir-2M is used to model the light-water reactor *Ruslan* and MAKET—the heavy-water LF-2/Lyudmila.[57]

Finally, the IKAR-S critical assembly at VNIIEF in Sarov has been built to support development of the IKAR-500 pulsed reactor.[58] The reactor, built as part of work on nuclear pumped lasers, is a relatively new project, so it is unlikely that VNIIEF would consider converting it to LEU.

Naval reactors

Naval reactor research and development has traditionally been one of the priority areas of the Soviet nuclear program. Today, Russia operates four critical facilities that were built as part of this effort.

Two critical assemblies at the Kurchatov Institute—Delta and Kvant—are used in a variety of experiments to study the physical characteristics of light-water naval reactors and as well as their shielding.[59] While the Kurchatov Institute facilities appear to focus on fundamental research, the two critical assemblies at the OKBM design bureau in Nizhniy Novgorod—ST-659 and ST-1125—are probably used to support development of new submarine and icebreaker reactors.

Beginning in the 1990s, Russia reduced the number of nuclear submarines and scaled down its naval reactor development programs. As a result, the Kurchatov Institute and OKBM have shut down a number of critical facilities involved in their naval reactor programs. Some prototype naval reactors in Obninsk and NITI in Sosnovy Bor have been decommissioned as well. For example, in 2017 all fuel was removed from the KV-2 facility at NITI.[60]

Even though Russia has made a commitment to use LEU in new icebreaker reactors, there is, as yet, no indication that it is considering discontinuing the use of HEU in reactors in submarine and military surface ships. Therefore, it is likely that Russia will keep the currently operational HEU critical assemblies in service as long as it continues its naval reactor research and development program.

Space reactors

The Soviet Union put significant effort into the development of nuclear reactors for space applications. Nuclear reactors of the Buk type provided thermoelectric power to 31 satellites of the US-A/RORSAT ocean radar reconnaissance system, launched between 1970 and 1988. In addition, the Soviet Union developed two thermionic space reactors—Topaz, flown into space twice in 1987, and Topaz-2/Yenisey, which has not been tested in space.[61]

Four critical assemblies that were used to support space reactor research continue to operate today—Aksamit and Narciss-M2 at the Kurchatov Institute and FS-1M and K-1 at the Institute of Physics and Power Engineering in Obninsk. The Kurchatov Institute also has two intact critical assemblies that were used in the program in the past—Chaika and Filin. The Gidra solution-based pulsed reactor, which was also built as part of the space reactor research program, appears to be scheduled for decommissioning.[62]

The future of these facilities is uncertain. While a nuclear power source was essential for a radar satellite (US-A/RORSAT type), Russia has no satellite under development that would require space reactors of the Topaz/Yenisey class.

Since 2010, Russia has been developing a new type of space power and propulsion system built around a nuclear reactor, known as a "Transportation and Power-Generation Module" (TEM in Russian).[63] The high-temperature gas-cooled fast-neutron reactor RUGK (after Russian "Gas-cooled Space-based Reactor Unit") is designed to provide up to 4 MWt/1 MWe of power. The electricity provided by the reactor would be used to power electric rocket engines.[64] The reactor uses high-density nitride fuel, most certainly 90% HEU (the actual level of enrichment has not been disclosed). The development effort is led by NIKIET but it is likely that the tests of the reactor prototype will be conducted at the NITI facilities in Sosnovy Bor.[65] It is extremely unlikely that the project can be terminated or converted to LEU. At the same time, the long-term prospects for the project are not clear. Indeed, the Russian space agency, Roskosmos, reportedly did not include the spacecraft that would use this technology in its 2016–2025 work plan.[66]

Irradiation experiments and nuclear laser research

The Soviet Union has built a large number of pulsed reactors and critical facilities designed to be used in various neutron and gamma-ray irradiation experiments.[67] These experiments include studies of the radiation hardness of military and civilian equipment as well as other applied and fundamental research. One area of research that has received particular attention is the development of nuclear-pumped lasers.

Most pulsed reactors that are used in irradiation experiments are operated by one of the two weapon laboratories. In addition, Rosatom operates two BARS-type pulsed reactors—BARS-6 at FEI in Obninsk and BARS-4 at NIIP in Lytkarino—which contain large amounts of HEU. These reactors may present an opportunity for consolidation that would help reduce the number of facilities that handle HEU. Since BARS-4 and BARS-6 are copies of the BARS-5 reactor at VNIITF in Snezhinsk, it might be possible to consolidate most of the research that uses their capabilities by moving it to Snezhinsk. In fact, BARS-6 at FEI in Obninsk is reportedly shut down and is being prepared for decommissioning.[68] BARS-4 has a utilization factor of about 0.8, however, and is the only pulsed reactor currently operated by NIIP, which has already shut down a number of its pulsed reactors.[69] Decommissioning of BARS-4 could seriously affect the institute's core mission.

The FS-1M zero-power reactor at FEI also contains substantial amounts of HEU. Built as part of the space-reactor research program, it is currently used with a FS- l-4.37.R critical assembly as a neutron source for radiation tests.[70] The prospects for a closure of this reactor are unknown.

Finally, the Priz pulsed reactor operated at TsFTI MO in Sergiyev Posad was built to test the radiation hardness of large military equipment. As a military organization, TsFTI MO probably provides dedicated experimental facilities, but the reactor itself is not unique, since it duplicates the capabilities provided by pulsed reactors in weapon laboratories. Indeed, it is possible that it has already been removed from TsFTI MO to VNIITF in Snezhinsk, where it was built.

Most of the pulsed reactors that are used in irradiation experiments are operated by the two weapon laboratories—VNIIEF in Sarov and VNIITF in Snezhinsk. They include six reactors that use metallic fuel, usually a uranium-molybdenum alloy, a large graphite-moderated reactor, BIGR (VNIIEF), and three homogenous solution reactors, VIR-2M at VNIIEF and IGRIK and YAGUAR at VNIITF. The reactors are used in a range of experiments that include irradiation of equipment and materials. Most of their work probably involves defense-related research. However, BIGR and YAGUAR have also been used in experiments that tested fuel elements for power reactors (including light water reactors). Also, a fair number of facilities are used to drive lasers—VIR-2M, BIGR, EBR-L, BARS-5 with the RUN-2 module and some that use small quantities of HEU, such as LM-8 or LUNA-2P. This work does not appear to be directly related to military applications; rather, it represents a case of fundamental research's taking advantage of the existing high-performance facilities.

The prospects for conversion or shutdown of these pulsed reactors are not clear. In most cases, the weapon labs upgrade and modernize their research facilities rather than shut them down. Moreover, a number of new HEU facilities are under construction or development. One of these projects is the IKAR-500 graphite-mode reactor that will be used in laser research at VNIIEF. As part of this project VNIIEF has already built the IKAR-S critical assembly.[71] The institute is also working on a UFN-P subcritical assembly that will be used together with the BIGR reactor in irradiation experiments.[72]

Given the nature of the work at weapon laboratories, it seems unlikely that shutting down or converting HEU-fueled research reactors would significantly reduce their security burden. Instead, they could become the centers for research work on applications that use high-performance pulsed reactors.

Criticality studies

The two weapon laboratories also operate research facilities that are used to study various critical systems—FKBN-2M in Sarov and FKBN-2 in Snezhinsk. Each of these critical assemblies has a set of core HEU fuel elements and can use a variety of other materials as well. These facilities are used to study various critical configurations, the properties of nuclear materials, and validate computational models. It is unlikely that they will be shut down, as they can play a significant role in defense-related work as well as in fundamental research. Indeed, VNIIEF is working to upgrade FKBN-2M; the new facility will be known as FKBN-3.[73]

Prospects for HEU minimization

Since the 1990s, Russia has shut down and decommissioned about 20 pulsed reactors and critical assemblies. At least two sites—the Krylov Institute in St-Petersburg and the Research Institute of Chemical Technology (VNIIKhT) in Moscow—appear to have been completely cleaned out. It is possible that all HEU has been removed from the Central Physical-Technical Institute of the Ministry of Defense (TsFTI MO) in Sergiyev Posad as well. Even though, in some cases, the material from decommissioned facilities was probably moved to local storage that would still significantly reduce the material's vulnerability.

To date, however, the shutdowns have not been part of a coordinated effort to minimize the use of HEU in response to security costs and proliferation concerns. The prospects for further reductions in the number of sites and facilities using HEU in critical and pulsed reactors will depend on a number of factors, including progress in converting steady-state reactors, re-evaluation of research and development programs using pulsed reactors, and consolidation of research activities at a smaller number of sites.

The five critical assemblies that support operations of existing steady-state research reactors are likely to remain in service as long as these reactors continue to use HEU fuel. Three of these critical facilities—FM PIK, FM SM-3, and FM MIR.M1—are co-located with their reactors, so they would not be shut down or converted independently. The situation with the two critical assemblies that support operations of the *Ruslan* and LF-2 tritium production reactors at the Mayak Plant in Ozersk is somewhat different as they are located at different sites and, in principle, could be shut down independently. Operations of *Ruslan* and LF-2 are supported by the Efir-2M critical assembly at the Kurchatov Institute and MAKET, located at the Institute of Theoretical and Experimental Physics (ITEF) both in Moscow, respectively. MAKET is the only operational HEU facility in ITEF. Its shutdown could therefore make possible a complete cleanout of the ITEF site.

The Kurchatov Institute is one of four Russian entities that operate five or more HEU critical facilities or pulsed reactors in addition to steady-state reactors. The other three are the two nuclear-weapon design institutes, VNIIEF in Sarov and VNIITF in Snezhinsk, and FEI institute in Obninsk. Motivating reductions in the use of HEU at these sites would be particularly challenging since a closure of any single facility may not bring substantial nuclear security benefits. Also, each of these organizations has a distinct research mission that cannot be easily moved to another site. This is especially true in the case of the weapon laboratories that conduct research on nuclear weapons modernization as well as safety and security of the existing arsenal. The Institute of Physics and Power Engineering (FEI) is expected to continue its work on fast neutron reactors, which will require it to continue operations of the BFS large critical facilities. As for the Kurchatov Institute, in addition to the Efir-2M critical assembly, it operates a number of facilities built to support space and naval reactor development, as well as the IR-8 and OR steady-state reactors. Overall, it is reasonable to assume that a complete elimination of HEU at these four sites is a rather long-term prospect.

It is conceivable that a re-evaluation of some legacy research programs could lead to a closure of a number of HEU facilities. For example, currently there seem to be no space applications that would require reactors of the Buk and Yenisei/Topaz-2 type. Therefore, some, if not all, of the research facilities that were built at the Kurchatov Institute to support this program—Aksamit, RP-50, Nartsiss-2M, Chaika, and Filin—could be decommissioned.

Consolidation of research work and eliminating duplication could present additional opportunities for reducing the number of HEU facilities. For example, it is possible that some of the critical assemblies that were built to study naval reactors—Kvant and Delta at the Kurchatov Institute and ST-659 and ST-1125 at OKBM in Nizhniy Novgorod—

could be shut down. Similarly, the BARS-5 pulsed reactor at VNIITF could probably accommodate most irradiation experiments as well as the work on nuclear pumped lasers that is currently carried out at BARS-6 at FEI in Obninsk and BARS-4 at NIIP in Lytkarino. And, if it has not been done already, irradiation experiments conducted at the TsFTI MO in Sergiyev Posad could be transferred to one of the weapon laboratories.

To summarize, Russia is unlikely to completely eliminate the use of HEU in its pulsed reactors and critical assemblies. It could do more, however, to reduce the number of sites and facilities that use HEU.

The federal program on development of new energy technologies and the development programs of Rosatom and the Kurchatov Institute, the primary agents of the federal program on development of new energy technologies, could provide a framework for considering such a consolidation.[74] The programs covering 2016–2020 give priority to the development of fast neutron reactors and associated technologies for a closed fuel cycle. It includes an upgrade of the BFS facilities and development of new types of nuclear fuel, the development of the TEM space propulsion and power-generation module as well as nuclear powered laser research. The classified section of the Rosatom innovation program includes support for the defense-related work at the weapon laboratories and other Rosatom institutions. Given that all these programs include support for development of new HEU research facilities, it appears that they do not currently explicitly include the goal of HEU minimization.

A long-term planning process that could include the decommissioning of HEU research facilities is the Federal Targeted Program "Nuclear and Radiation Safety in 2016 and through 2020." However, this program as well as its predecessor, the 2008–2015 Federal Targeted Program, focuses primarily on management of spent fuel and on the radioactive waste legacy of the nuclear industry, so it would not normally address critical assemblies and pulsed reactors.[75] Nevertheless, the 2008–2015 program did include decommissioning of, the RG-FS and BR-1 HEU-fueled reactors at the FEI institute in Obninsk, BARS-2 at NIIP, and critical assemblies at the Krylov Institute in St-Petersburg.[76] The current program does not seem to include dedicated funds for decommissioning HEU-fueled research facilities, although it may result in some HEU minimization.[77]

Taken together, the federal programs on development of new energy technologies and on nuclear and radiation safety constitute a mechanism that could address the issue of HEU use in research facilities, including critical assemblies and pulsed reactors, in a systematic way. Using them in this manner would, however, require a high-level commitment to HEU minimization and a coordination process for identifying facilities that can be decommissioned and cleaned out.

2A APPENDIX
Pulsed reactors, critical and subcritical assemblies

National Research Centre Kurchatov Institute, Moscow

The Kurchatov Institute operates a number of research reactors as well as critical and subcritical facilities. It hosts two homogenous solution reactors—Argus and Gidra. Argus was converted to LEU in 2014.[78] Gidra, a reactor of the IIN-3 type, which has about 3.2 kg of 90% HEU in its active zone, appears to be scheduled for shutdown.[79] The reactor was built in 1971 to test fuel elements of space power reactors, but is used in other applications as well.[80]

There are a number of other critical assemblies that are also used in applications related to space power and propulsion. The Aksamit critical facility is used in the development of thermionic reactor convertors.[81] The facility can simulate a variety of core configurations using a set of 90% enriched HEU nitride fuel elements. Its total HEU inventory is about 210 kg.[82]

The same space-reactor division also hosts the RP-50 critical assembly, which can work as part of Aksamit. It appears to be a prototype space reactor developed jointly with Krasnaya Zvezda that probably also uses 90% enriched uranium nitride fuel.[83] The amount of HEU associated with the RP-50 is not known, but it is probably on the order of 100 kg.

Another space-reactor prototype is the Narciss-M2 critical assembly used as a mock-up of the core of the Yenisey/Topaz-2 thermionic space reactor. The assembly uses uranium dioxide-based fuel with 96% HEU. The amount of HEU in the assembly is estimated to be about 27 kg.[84]

The Kurchatov Institute also works on the development of high-temperature gas-cooled reactors. Three critical assemblies appear to be associated with this work. In the past, the Filin and Chaika critical assemblies were part of the Iskra facility, which was used to study space propulsion.[85] Iskra appears to have been dismantled, but the two critical assemblies, although not in active use, are intact. They use 90% enriched HEU. Chaika uses uranium nitride fuel, Filin uses uranium carbide fuel.[86] The amount of HEU in these critical assemblies appears to be on the order of tens of kilograms.

The Astra critical assembly is a mockup of a gas-cooled power reactor that uses pebble-type graphite-uranium fuel with 21% HEU. The total amount of HEU is about 120 kg, containing about 25 kg of uranium-235.[87]

Two other critical assemblies were used in space reactor related research—Romashka with thermoelectric and Topaz-2 with thermionic converters. They were shut down and decommissioned in 1966 and 1986, respectively.[88]

The Kurchatov Institute has also been participating in the development of naval light-water propulsion reactors. The two operational critical facilities associated with this activity that are still in service are Delta and Kvant, built in 1973 and 1990, respectively. Delta uses uranium dioxide fuel with enrichments of 80% and 90%. Kvant uses 90% HEU fuel (but may also use fuel with enrichments as low as 5%).[89] Each may have about 100 kg of HEU.

Two other critical assemblies used as mock-ups of naval propulsion reactors are being decommissioned. The SF-1 critical assembly, built in 1972, used HEU fuel with enrichments ranging from 21% to 90%.[90] The SF-7 critical assembly reportedly uses 80% enriched uranium-zirconium alloy fuel. SF-7 became operational in 1975.[91] SF-1 is a pressurized water assembly (up to 300 °C and 200 atm), while SF-7 is low-temperature facility with water temperatures of less than 90 °C.[92] The amount of material in these facilities is not known, but they are likely to use about 100 kg of HEU each. Two other critical assemblies linked to the propulsion reactor research, SF-3 and SF-5, were shut down in the 1990s.

Finally, Efir-2M, built in 1973, is a physical model of the *Ruslan* water-moderated tritium-production reactor that can also be used to model a variety of core configurations. It uses 90% enriched fuel and probably contains about one hundred kilograms of HEU.[93]

A number of critical assemblies at the Kurchatov Institute have been shut down and decommissioned. In addition to the Romashka, Topaz-2, Iskra, SF-3 and SF-5, mentioned above, these include the FM MR physical model of the MR reactor (itself shut down in 1993), Mayak and UG. FM MR and its parent reactor, MR, are known to have used 90% HEU fuel. UG, a graphite-moderated facility that was used to study the core designs of plutonium production reactors (which probably means that it had some 90% HEU fuel elements associated with it) is in "safe storage" mode.[94] There is little information about the Mayak critical facility that operated at the Kurchatov Institute starting in 1967 and which was shut down in 2000. It used uranium-aluminum alloy fuel, which may have been HEU-based.[95]

All-Russian Scientific Research Institute of Experimental Physics (VNIIEF), Sarov

VNIIEF, one of the two main Russian nuclear weapon laboratories, operates a large number of pulsed reactors and critical assemblies.

The BIGR is a large fast-neutron pulsed reactor. Its core consists of a hollow cylindrical fuel element made from a ceramic that combines uranium dioxide and graphite. The reactor core contains 400 kg of uranium-235 in 90% HEU.[96] One use of this reactor is as a neutron source for the LM-4 nuclear pumped laser facility.[97] VNIIEF is considering building a UFN-P subcritical assembly that would be driven by neutrons from BIGR.

UFN-P would use three different core configurations with a total amount of about 25 kg 90% HEU in uranium oxide.[98]

BR-1M is one of the series of pulsed reactors with cylindrical cores that have been developed by VNIIEF for criticality experiments and irradiation of various samples. The mass of the BR-1M core, assembled from uranium-molybdenum alloy with 90% HEU and 9% Mo content, is 176.1 kg.[99] This corresponds to about 160 kg of 90% HEU.

The BR-K1 reactor also uses U-Mo alloy with 9% Mo content in its fuel elements. However, the uranium enrichment is 36%. The mass of the reactor core is 1511 kg, containing 500 kg of uranium-235 in about 1400 kg of 36% HEU.[100]

The third reactor in the series, BIR-2M, became operational in 1965 (as BIR) and may have been decommissioned at some point after 2006.[101] The reactor used U-Mo alloy fuel elements with 6% Mo content and 85% HEU. The mass of the core was 121 kg containing about 97 kg of uranium-235 in 114 kg of 85% HEU.[102] In 1974, the BIR reactor was used in combination with the PKS subcritical assembly to study linked reactor systems.[103] The PKS assembly appears to have been dismantled.

The GIR-2 pulsed reactor was built at VNIIEF in 1984 (as GIR) for use in criticality and irradiation experiments. The reactor uses spherical fuel elements made from U-Mo alloy (9% Mo content). The total mass of the reactor core is 178 kg. Some elements use 36% HEU while others use 90% HEU. Some reports, however, suggest that all were made from 90% HEU.[104] If so, the amount of 90% HEU in the reactor would be about 162 kg.

VNIIEF also developed a line of FKBN critical facilities. The first, FKBN, became operational in 1949 and was later replaced by FKBN-1 and FKBN-2.[105] The most recent modification, FKBN-2M, became operational in 1997.[106] The total mass of the components used by the facility is probably several hundred kilograms. A similar facility at VNIITF uses components containing about 270 kg 90% HEU.[107]

VNIIEF also operated the MSKS critical facility, which shared the building (and the fuel elements) with FKBN.[108] It appears that MSKS has been dismantled.

Since 1965 VNIIEF has been operating the VIR homogenous solution pulsed reactor. The most recent modification, VIR-2M, became operational in 2001. The reactor uses an aqueous solution of 90% enriched uranyl sulfate.[109] The mass of uranium-235 in the active zone is 7.8 kg, corresponding to about 8.7 kg of 90% HEU.[110]

The VIR-2M reactor is used as a source of neutrons for various experiments including the LUNA-2M and LUNA-2P experimental laser facilities.[111]

Since 2008, VNIIEF has operated the IKAR-S critical assembly that was built to model the core of the proposed IKAR-500 reactor. The assembly uses U-Al dispersion fuel with 90% HEU. The mass of uranium-235 in the core is 24 kg (in 690 kg of fuel). One of the applications of the reactor is the study of nuclear pumped lasers.[112]

All-Russian Scientific Research Institute of Technical Physics (VNIITF), Snezhinsk

VNIITF is the other main Russian nuclear weapon laboratory. Like VNIIEF, it operates a number of pulsed reactors and critical assemblies for weapon-related and other experiments.

VNIITF operates two homogenous solution pulsed reactors—IRGIK and YAGUAR. The reactors, which reached criticality in 1976 and 1990 respectively, use an aqueous solution of 90% enriched uranyl sulfate. IGRIK and YAGUAR contain about 6 and about 18 kg of HEU, respectively. [113]

BARS-5 is a two-core reactor for irradiating large samples. Its fuel elements contain 90% enriched uranium-molybdenum alloy (10% Mo by weight).[114] The reactor can operate with three different core configurations that share a common set of elements. The total mass of the complete element set for one core is about 160 kg, which corresponds to about 290 kg of 90% HEU in two reactor cores.

BARS-5 can work together with the RUN-2 subcritical neutron multiplier that was built in 1994. RUN-2 contains about 50 kg of 90% enriched HEU in uranium-molybdenum alloy (10% Mo).[115]

VNIITF also created the EBR series of pulsed reactors. The only one operating today is EBR-L, which reached first criticality in 1976 (as EBR-200M). It is used in the development of nuclear pumped lasers.[116] Its core consists of semi-spherical elements made of 90% enriched uranium-molybdenum alloy (3% Mo). The total mass of the elements in EBR-200M is 74.5 kg.[117] Assuming that EBR-L uses similar fuel elements, the amount of 90% HEU associated with the reactor is about 72 kg.

EBR-L can work with the RUS-V reactor in a two-core system. RUS-V has also been used independently for irradiation of large pieces of military equipment. The reactor has two cores made of 90% enriched uranium-molybdenum alloy (3% Mo) with a total mass of about 100 kg.[118]

For criticality studies, VNIITF uses the FKBN-2 critical facility, which reached first criticality in 1971 (as FKBN-M, replacing its predecessor, FKBN, which was dismantled). The facility uses four sets of spherical elements plus a set of cylindrical elements, ROMB, that includes plutonium as well as HEU components. The uranium elements are made of HEU with about 90% enrichment. The total mass of HEU in all sets is about 272 kg. The mass of plutonium in the elements of the ROMB set is about 20 kg. [119]

Three additional pulsed reactors that were built in VNIITF—BARS-2, BARS-3, and BARS-4—were transferred to the Scientific Research Institute for Instruments (NIIP) at Lytkarino. Other HEU facilities that were operated by VNIITF included the ELIR homogenous solution reactor (1966–1984), and the FKBN-I facility that used various EBR-type active zones. All these facilities appear to have been dismantled.

Institute of Physics and Power Engineering (FEI), Obninsk

FEI has a number of HEU critical assemblies and pulsed reactors that are used in a variety of applications. The two critical assemblies, BFS-1 and BFS-2, appear to contain the largest amount of HEU in Russia's civilian nuclear sector.

The BFS-1 and BFS-2 became operational in 1962 and 1969, respectively, in order to provide the capability to create full-scale models of fast neutron reactors with a variety of core configurations and fuels.[120] Their fuel elements are made of stacks of small disks of clad uranium metal, uranium dioxide and plutonium dioxide, as well as thorium and neptunium. The uranium disks contain depleted and natural uranium as well as uranium with enrichments of 21%, 36%, and 90%. According to one estimate, the HEU associated with the BFS facilities includes as many as 8.7 tons of 90% and 36% enriched HEU in metal and dioxide form.[121] However, these numbers may not take into account recent removals of fissile materials from the site. This estimate assumes that the HEU stock at the BFS-1 and BFS-2 facilities includes about 700 kg of 90% HEU and about 3000 kg of 36% HEU.

Another FEI facility, the FS-1M critical assembly, was built in 1970 and was used to study neutronic characteristics of thermionic fast neutron reactors, probably for space applications. Since its modernization in 2004, it has been used for irradiation tests and in the calibration of neutron measurements. It uses 90% enriched uranium dioxide fuel. The amount of uranium-235 in the core is 228 kg, corresponding to about 253 kg of HEU.[122]

The institute also houses the BARS-6 pulsed reactor, identical to BARS-4 operated by NIIP in Lytkarino and similar to BARS-5 at VNIITF in Snezhinsk. Like BARS-4, the reactor has a single set of fuel elements made of uranium-molybdenum alloy with 10% molybdenum content. The total amount of 90% HEU in the reactor is about 220 kg.[123] The BARS-6 reactor is used to drive the OKUYAN subcritical assembly that was built in 1999 as a model of a laser with nuclear pumping. The OKUYAN fuel elements are coated with a very thin layer of uranium-235. The total amount of uranium is estimated to be about 1.2 kg of 90% HEU. BARS-6 and the OKUYAN assembly are part of the "Stend B" experimental facility.[124] As of 2015, operations at the facility had been discontinued and it is being prepared for decommissioning.[125]

One critical assembly in Obninsk, K-1, was built in 1989.[126] The assembly uses HEU fuel, but there is little information about the level of enrichment or the amount of material. K-1, which appears to be used in space-power projects, is currently undergoing reconstruction.[127] For the purposes of this study, the assembly is estimated to contain about 50 kg of 90% HEU.

In addition to the reactors and critical assemblies listed above, there are a number of HEU facilities that have been shut down or decommissioned. One is the BR-1 critical assembly. Built in 1955 as the first Soviet fast reactor, BR-1 used HEU fuel, but was converted to plutonium.[128] UKS-1M, was a subcritical assembly used to study lasers with nuclear pumping. The assembly was estimated to contain about 33 kg of uranium-235. The UKS-1M facility also included a "small U-Mo fast reactor" as a neutron source.[129] That facility appears to have been shut down.

Other shutdown and decommissioned HEU facilities include "Stend T-2" and Strela, used in the space-reactor development program. RF-GS, an aqueous solution pulsed reactor, was shut down in 2003. The KOBR, SGO and PF-4 HEU facilities were used in criticality experiments. Altogether, the Institute of Physics and Power Engineering operated more than 20 critical assemblies including PNFT, F, FG-5, GROT-2, V-1M, and PS-2, all of which appear to have been shut down. The material associated with these facilities was probably transferred to the institute's fissile material store.

Research Institute of Atomic Reactors (NIIAR), Dimitrovgrad

NIIAR has two critical assemblies built as physical models of the cores of reactors operated by the institute. The first, FM MIR.M1, became operational in 1966, the second, FM SM-3, has been in operation since 1970. Like the reactors, the critical assemblies use 90% enriched fuel. The amount of HEU in these facilities is estimated to be 20 kg for FM MIR.M1 and 40 kg for FM SM-3.[130]

Institute of Theoretical and Experimental Physics (ITEF), Moscow

ITEF operates one critical assembly, MAKET, which is a heavy-water critical assembly that was built in 1976 to support development of the LF-2/Lyudmila tritium production reactor. The assembly has also been used to model other heavy-water reactor cores. It uses fuel elements of the TVS type that contain 90% enriched uranium. Some fuel elements have reduced uranium-235 content to simulate fuel burnup.[131] A fully loaded zone with fresh fuel would contain about 25 kg of 90% HEU. The total amount of HEU associated with the assembly is most likely on the order of 100 kg or more.

Until about 2011, the institute worked to develop the ELYaNG (electro-nuclear neutron generator) accelerator-driven neutron source. The subcritical target assembly was expected to use the 90% HEU fuel elements of the decommissioned TVR reactor.[132] This project, however, appears to have been cancelled.

Scientific Research Institute for Instruments (NIIP) in Lytkarino

The primary mission of this institute is the development of radiation-hardened electronic equipment, some of which is designed for military applications.[133]

The institute has two nuclear facilities in operation—the IRV-M2 nuclear reactor and the BARS-4 pulsed reactor. BARS-4 is an aperiodic, two-core, self-quenching reactor that can provide short neutron and gamma radiation bursts. The reactor, which is similar to BARS-5 and BARS-6, was built in 1969 at VNIITF and was transferred to NIIP in 1970.[134]

The two reactor cores are assembled from 90% enriched uranium-molybdenum alloy fuel elements. The BARS-4 reactor uses a set of fuel elements with a total mass of about 123 kg.[135] Since the alloy contains 10% molybdenum, the amount of HEU in the two cores of the reactor is, therefore, about 220 kg.

In the past, NIIP operated four other pulsed reactors that used HEU. BARS-2, built in VNIITF in 1969, was transferred to the institute in 1970.[136] The BARS-3M reactor, which NIIP operated during 1988–1997, was a modified BARS-3 reactor that was built at VNIITF.[137] A different pulsed reactor, TIBR-1M, was built in VNIIEF and moved to Lytkarino in 1975.[138] Finally, during 1972–2005 the institute operated the IIN-3M solution reactor. All these reactors have been shut down and decommissioned with the material removed from the site.[139]

In addition to the radiation hardness research, NIIP was involved in the development, testing, and decommissioning of various experimental reactors. The Stend T facility was used for experiments for the Buk and Yenisey space reactors.[140] Two experimental aircraft-propulsion reactors, VVRL-02 and VVRL-03, were brought to NIIP from the test site at Semipalatinsk for decommissioning and dismantlement. All these reactors have been dismantled and decommissioned.

Scientific Research and Design Institute of Power Engineering (NIKIET), Moscow

NIKIET is the lead contractor for the development and operations of various types of nuclear reactors.[141] The institute is working on the MBIR fast neutron research reactor that is expected to replace BOR-60 as well as on the BREST fast neutron power reactor.

NIKIET operates an HEU subcritical assembly, FS-2, that is located at the Bauman State Technical University and used for research and training. The core contains about 2.9 kg of 36.7% HEU. FS-2 was shut down for modernization in 1998 and restarted in October 2015.[142]

As of 2014, NIKIET was in the process of testing various components of the RUGK reactor of the TEM space power and propulsion system at the Skif critical facility.[143] First fuel assemblies for the reactor were produced in 2014, but it appears that they have not been tested yet.[144] Rosatom plans to complete the reactor development work in 2018.[145]

Petersburg Nuclear Physics Institute, Gatchina

The institute operates one critical assembly, FM PIK, which is used as a physical model of the PIK reactor. The facility became operational in 1983. It contains about 30 kg of 90% HEU in 18 fuel assemblies.[146] In the past, the institute also operated the FM VVR-M critical assembly, which was used as a physical model of the VVR-M reactor collocated there.[147]

Krasnaya Zvezda State Enterprise, Moscow

Krasnaya Zvezda is the Rosatom organization that manufactured the Buk and Yenisey space reactors.[148] However, the reactors were fueled elsewhere, so the enterprise did not have nuclear material on site. Also, Krasnaya Zvezda produced Argus-type solution reactors, also without fuel.[149] The enterprise continues its work on space reactors, but it does not seem to have any HEU.

Central Physical-Technical Institute of the Ministry of Defense (TsFTI MO), Sergiyev Posad

TsFTI is the leading military institute conducting research on the effects of nuclear weapons. It operated several pulsed reactors. BARS-1, built in VNIITF, was transferred to TsFTI in 1966 but has been decommissioned. Another pulsed reactor, Priz, also designed and built in VNIITF, operated at TsFTI beginning in 1970. It was used to study effects of nuclear explosions on large military equipment (such as tanks). The reactor used uranium-molybdenum alloy fuel elements with a total mass of about 50 kg of 90% enriched uranium.[150] The current status of the reactor is unknown. For the purposes of this report's estimate of HEU stocks, it is assumed to be operational, but it is possible that the reactor has been dismantled or removed to VNIITF.

Machine-Building Plant (MSZ), Electrostal

The Electrostal plant, also known as Elemash, produces fuel for research and power reactors including naval propulsion reactors. It has been operating seven critical facilities, Stend-1 to Stend-7. Two, Stend-2 and Stend-3, were used to test fuel assemblies for naval reactors. These facilities, which did not normally have their own fuel, were decommissioned in 2002 and 2012, respectively.[151] The only facilities that remain in operation, Stend-4 and Stend-5, are used to test LEU fuel.[152]

All-Russian Research Institute of Chemical Technology (VNIIKhT), Moscow

VNIIKhT operated one subcritical assembly, SO-2M, fueled with 36% enriched HEU.[153] The assembly was shut down and decommissioned in 2011.[154]

Krylov Central Research Institute, St-Petersburg

The Krylov Institute used the G-1 and MER critical assemblies and R-1 subcritical assembly, which are believed to have used HEU. All were shut down in 2002 and any HEU that may have been associated with them was removed by 2007.[155]

Experimental Design Bureau of Machine-Building (OKBM), Nizhniy Novgorod

OKBM operates two critical assemblies that are used to support the development of light-water naval reactors. The ST-659 began operations in 1963 and the ST-1125 in 1975. Both facilities are said to use fuel with variable uranium-235 content, which probably corresponds to the range of 21–45% used in naval reactors.[156] Two other critical assemblies at OKBM, ST-659L and ST-1120, which probably also used HEU, have been shut down.

3 Prospects for conversion of Russia's HEU-fueled research reactors

Introduction

Nuclear research reactors, including steady state and pulsed reactors, and critical and subcritical assemblies are used in the development of nuclear weapons and to do irradiation tests of candidate materials for use in power reactors. Neutrons from research reactors have also found uses in other sectors, such as medicine and biology. Furthermore, large amounts of experimental data relevant to reactor core design, which can be used in computer models to solve many additional research problems, have also been accumulated.

The number of research reactors in the world increased rapidly starting in the 1950s and reached a maximum of 390 in the 1970s.[157] In the early 1980s, the number of nuclear research reactors began to decline as the retirement rate of old reactors exceeded the number of new research reactors being brought on line. Eventually, construction of new research reactors virtually ceased and many older and less capable reactors were decommissioned. As of mid-2017, there were 247 active research reactors worldwide, with only 9 under construction and 10 planned, while 159 had been shut down and 366 decommissioned.[158]

A priority for researchers and designers has been to maximize the neutron flux (neutrons per second per square centimeter) available in irradiation channels for a given reactor power. This has put a premium on compact cores, which are most easily achieved by using HEU. As a result, prior to about 1980, the majority of research reactors in Russia and in the United States were fueled with weapon-grade HEU, enriched to 90–93%.

In the late 1970s, however, it was recognized by both the United States and the Soviet Union that exporting HEU fuel created proliferation risks. Both countries initiated programs to lower the enrichment level of the fuel they exported to below 20% uranium-235. The Soviet program proceeded in two stages: in the first stage the enrichment level was reduced to 36% and in the second to below 20%. In 1993, Russia and the United States began collaborating on the development of low-enriched fuel (less than 20% enrichment).[159] This program was part of the Reduced Enrichment in Research and Test Reactors program, RERTR (see Chapter 4 for details).

The main focus of Russia's program has been on the development and production of fuel for Soviet-supplied reactors in third countries. Organizations participating in this program include the TVEL Fuel Company, the Scientific Research and Design Institute of Power Engineering (NIKIET), the Bochvar All-Russian Scientific Research Institute for Inorganic Materials (VNIINM), the Novosibirsk Chemical Concentrate Plant (NCCP), the Research Institute of Atomic Reactors (NIIAR), the Institute of Physics and Power Engineering (IPPE or FEI), the Institute of Reactor Materials, the National Research Centre Kurchatov Institute, and the Petersburg Nuclear Physics Institute. The three-phase program called for the development of fuel with increasing densities:

- Phase 1: fuel using UO_2 dispersed in an aluminum matrix;
- Phase 2: fuel based on uranium-molybdenum alloys dispersed in an aluminum matrix; and
- Phase 3: monolithic uranium-molybdenum alloy fuel.

Work on the first phase of the program was largely completed by 2000. The production of fuel assemblies for the VVR-M2 and IRT-4M pool-type research reactors, with enrichment below 20%, 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.

This laid the foundation for the May 2004 United States-Russian agreement on a Russian Research Reactor Fuel Return Program, RRRFR, to remove Russian-made fresh and spent HEU research reactor fuel from third countries to Russia while those reactors were being converted to LEU fuel. Fourteen countries have participated in the program: Belarus, Bulgaria, the Czech Republic, Hungary, Germany, Kazakhstan, Latvia, Libya, Poland, Romania, Serbia, Ukraine, Uzbekistan, and Vietnam (see Chapter 5).

Despite the fact that Russia has more HEU-fueled research reactors inside its borders than any other country, the task of converting Russian reactors to LEU fuel was not addressed until very recently. Discussions among Russian experts started in connection with a December 2010 agreement between Rosatom, the state corporation that manages most of Russia's nuclear activities, and the U.S. Department of Energy to conduct a preliminary study on the possibility of converting six Russian research reactors: Argus, OR, and IR-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).[160] This chapter describes the progress of this program as well as efforts to convert Russian research reactors from HEU to LEU fuel.

Russia's civilian research reactors

Russia's civilian research reactors are employed across a wide range of scientific, technical and practical applications from fundamental research to research and development of nuclear power reactors and the production of medical isotopes and materials for electronics. This has led to a variety of reactor types and specifications. These research reactors differ in core design, power output, mode of operation, cooling system, moderator, reflector materials, and fuel enrichment. Appendix A of this report lists the Russian reactors and other facilities that use HEU fuel.

This chapter considers civilian research reactors, which are licensed by the Russian Federal Service for Ecological, Technological, and Nuclear Oversight (Rostekhnadzor).

According to Rostekhnadzor data, as of the end of 2013, 22 civilian research reactors had operating licenses.[161] This number appears to include the IRV-M2 reactor that is undergoing reconstruction and has a construction license.[162] In addition, one reactor, BR-10, was in the final shutdown mode and five reactors had decommissioning licenses: MR, RBT-10/1, AM-1, TVR, and AST-1/Arbus.[163] Among civilian reactors with operating licenses, three use LEU fuel (F-1, IR-50, and VK-50) and one, IBR-2M, uses plutonium-based fuel. One reactor, Argus, has been converted to LEU fuel in 2014.

Two HEU-fueled reactors—IRT-MEPHI and Gamma—had no operating licenses in 2013. IRT-MEPhI is undergoing refurbishment and is expected to apply for an operating license once the process is completed. Gamma is being decommissioned. However, it is not clear if these reactors are included in the total of 22 reactors with operating licenses listed by Rostekhnadzor.

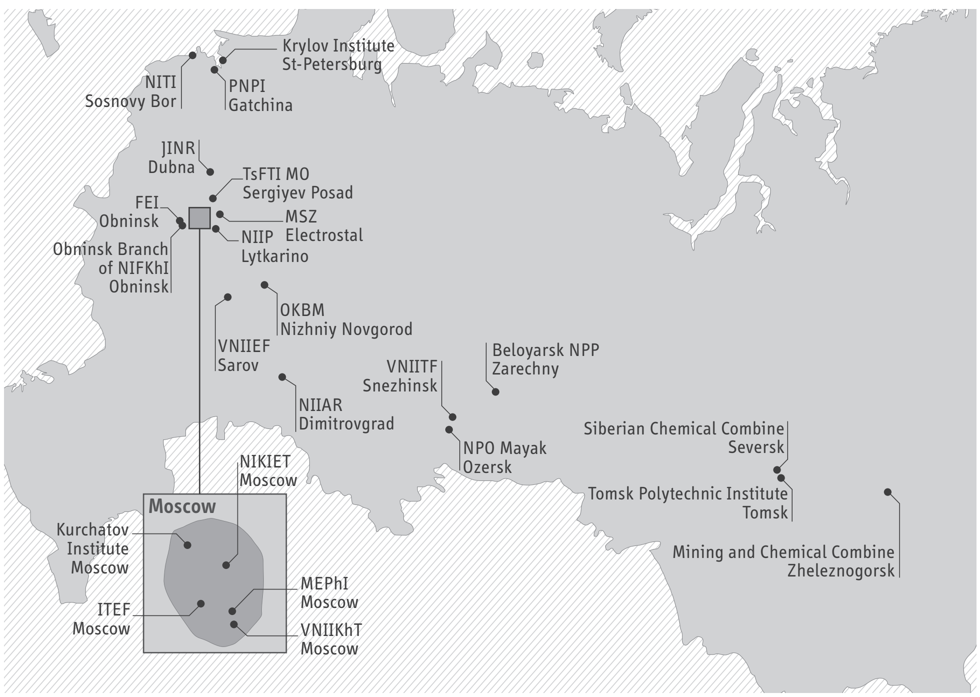

Figure 3.1. Reactors and research facilities that use HEU or used HEU in the past.

Most of the reactors licensed by Rostekhnadzor are steady-state reactors that are potential candidates for conversion to LEU. These reactors are listed in Table 3.1, their locations are shown on Figure 3.1. Two are pulsed reactors, BARS-4 and BARS-6, which are considered in Chapter 2 along with other pulsed reactors and critical assemblies.

Reactor	Uranium-235 in core (kg)	Enrichment (%)	Annual uranium-235 requirements (kg, estimate)
National Research Centre Kurchatov Institute, Moscow			
IR-8	4.4	90	2.2
Gidra	3.2	90	—
OR	3.8	36	0.08
Scientific Research Institute for Instruments (NIIP), Lytkarino			
IRV-M2	4.8	36	0.8
Petersburg Nuclear Physics Institute, Gatchina			
VVR-M	9.7	36, 90	13
PIK	27.5	90	83
Research Institute of Atomic Reactors (NIIAR), Dimitrovgrad			
SM-3	36	90	79
RBT-6	34	90	—
RBT-10/2	44	90	—
MIR.M1	20	90	39
BOR-60	up to 150	45–90, Pu	39
Institute of Reactor Materials (IRM), Zarechnyy			
IVV-2M	6.7	90	9.6
Tomsk Polytechnic Institute, Tomsk			
IRT-T	6.7	90	2.2
Moscow Institute of Physics and Engineering (MEPhI), Moscow			
IRT-MEPhI	5.2	90	0.25
Obninsk Branch of the Karpov Scientific Research Institute of Physical Chemistry (NIFKhI), Obninsk			
VVR-Ts	7.6	36	8
Total	~350		~276

Table 3.1. Civilian research reactors with HEU fuel in Russia.

Prospects for conversion

The joint U.S.-Russian effort to minimize the use of HEU in reactors in Russia achieved its first conversion in July 2014, when the Argus reactor at the Kurchatov Institute began operations with LEU.[164] Argus is a solution reactor with negligible fuel consumption.

Another solution reactor on the list, Gidra, also operated by the Kurchatov Institute, is scheduled for shutdown and, therefore, will not be converted. The decommissioning of Gidra was included in the Federal Program "Nuclear and Radiation Safety in 2008 and through 2015" and the license that was issued to the reactor in 2009 expired in December 2014.[165]

Four reactors, SM-3, MIR.M1, BOR-60 and PIK, are responsible for about 90% of the total annual HEU consumption. This annual HEU consumption would reach almost 300 kg/year when and if the PIK reactor operates at full power. Only MIR.M1, was considered for joint U.S.- Russian conversion, however. SM-3 and PIK use unique fuel and developing a suitable LEU fuel alternative for these reactors has not yet been addressed. BOR-60 is a fast-neutron reactor and cannot operate on LEU fuel. It is projected to continue operations until 2018–2020, when it will be replaced by a new fast reactor, the MBIR.[166]

Two reactors operating at NIIAR, RBT-6 and RBT-10/2, cannot be independently converted as they are fueled with partially irradiated fuel from the SM-3 reactor.

That leaves eight reactors to be discussed, five of which were among the six reactors chosen for the joint U.S.-Russian study that was launched in 2010.

The choice of the six reactors was based on the availability of suitable LEU fuel. As has already been noted, Argus had already been converted. Conversion of the MIR.M1 reactor would make a significant contribution towards reducing Russia's use of HEU in research reactor fuel. Preliminary analysis showed that conversion is technically feasible, but conversion is not being considered in the ongoing modernization of this reactor.[167]

Conversion of the IR-8, IR-T, IRT-MEPhI, and OR reactors would all be possible with uranium-molybdenum dispersion fuel that is under development. However, Russia does not see their conversion as a high priority at the moment. Also, in the case of the IR-T reactor, the operator is concerned that the neutron spectrum would be "hardened" (made more energetic) as a result of the conversion. This would make the reactor less suitable for silicon transmutation doping, which provides the main source of funding for the reactor's operation.[168]

The remaining four reactors in Table 3.1 are IRV-M2, VVR-M, IVV-2M and VVR-Ts. The first four could all potentially be converted to LEU using uranium-molybdenum dispersion fuel. The fifth, the VVR-Ts, is similar to Kazakhstan's VVR-K reactor for which LEU fuel has already been developed. Testing of the new fuel assemblies (known as VVR-KN) produced at the Novosibirsk Chemical Concentrate Plant started in 2012.[169] Conversion of the reactor to the new fuel assemblies will not affect the operating characteristics of the VVR-K.

The lack of interest on Russia's part in the conversion of its own HEU-fueled research reactors can be explained by a number of interrelated reasons. Most have been operating for more than 30 years and the utilization factor of some is extremely low. In recent years, a third of the Russian research reactors were used less than 10% of the time and only slightly more than one-third of the reactors have been used more than half 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 that are rarely used or nearing the end of their projected lives are not interested in conversion.

Another reason for the lack of interest in conversion is related to the fact that the research reactors that do have high utilization factors (SM-3, MIR.M1) are heavily engaged in supporting fast-neutron reactor development. According to Russian experts, this requires research reactors able to generate neutron fluxes on the order of 10^{16} n/(cm^{2}sec).[170] A new multi-purpose 150 MWt sodium-cooled fast-neutron research reactor, MBIR, is being built and is scheduled to start-up in 2019. It will be fueled either by a mixture of 93% HEU and plutonium oxide plus 7% uranium metal, 93% (U-Pu)O_2 + 7% U metal, or by nitride fuel (PuN+UN).[171]

The existing reactors that can provide a neutron flux close to the desired level are SM-3, RBT-6, RBT-10/2, MIR.M1, PIK, VVR-M, IR-8, IVV-2M, all of which use highly enriched fuel. Conversion of some of these reactors would require not only the development and testing of LEU fuel, but in some cases also the reconstruction of their cores.[172] This would require time and significant financial expense by reactor operators, who may not have the necessary resources, and it could also adversely affect the success of ongoing nuclear power development programs. Finally, conversion has not received much interest because, unlike U.S. policy, Russian policy is less driven by concerns about nuclear terrorism.

The absence of a government program for the conversion of Russia's research reactors may be explained by a combination of the considerations above. Without such a program, supported by federal funding, it is unrealistic to expect reactor owners to initiate and fund conversion of their research reactors. Obviously, the development of such programs would require an analysis of costs and benefits for converting each of the operating research reactors, based on its expected remaining service life.

Although Rosatom has low interest in the conversion of its own research reactors it is interested in continuing in the cooperative conversion work with the U.S. in other countries. The Russian Research Reactor Fuel Return (RRRFR) program, which was recently extended to 2024 is an example of successful U.S.-Russian cooperation.[173] Rosatom is currently collecting and summarizing the necessary decision-making information, to decide on whether or not to include spent fuel from Russian research reactors in the RRRFR program. Russia's spent research reactor fuel storage facilities hold about 14,000 fuel assemblies and fuel rods of different types, containing several tons of HEU. About 80% of this spent HEU fuel is stored at the Institute of Physics and Power Engineering (Obninsk) and NIIAR (Dimitrovgrad).[174]

Recommendations

In supporting the final communiqués of the Nuclear Security Summits held in 2010, 2012 and 2014, Russia made clear that it recognized the urgency of converting research reactors to LEU fuel and minimizing the use of HEU. It would, therefore, seem advisable for Russia to include HEU minimization in its national program for the maintenance and development of its fleet of research reactors.

This program could begin with an audit of all Russian nuclear research reactors to identify which are no longer needed and to inform decisions on the construction of new facilities.

Sources of funding for the decommissioning of unnecessary nuclear research installations, the conversion of research reactors, and the construction of new research facilities would need to 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 its civilian sector.

3A APPENDIX
Russian civilian research reactors with HEU fuel

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

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

The reactor core consists of 85 to 124 fuel assemblies, with fuel composed of either uranium dioxide enriched to 90% or a mixture of uranium and plutonium with uranium enrichment in the range 45–90% and a concentration of plutonium up to 30%. The reactor core is estimated to contain up to 150 kg of uranium-235.[175] In recent years, the reactor has operated at a power of 53 MWt . Its utilization factor (measured by the ratio of the number of full days of full power operation to the number of days in the calendar year) has recently ranged between 0.60 to 0.65. Assuming a discharged fuel burn-up of 30%, its annual uranium-235 consumption would be up to 39 kg.

The 20-year design lifetime of the BOR-60 reactor has been exceeded twice. In 2009, the reactor was supposed to be renovated and its life extended until 2030. In 2010, Rosatom made a decision to extend operation until completion of the multipurpose fast neutron research reactor (MBIR) currently projected to be commissioned in 2019–2020.[176]

The unique characteristics of BOR-60 and its decommissioning timeline exclude the possibility of converting it to LEU fuel.

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

SM-3 is a high-flux, water-cooled and moderated, tank-type reactor with a thermal power of 100 MW. It is designed primarily for the production of transuranium elements and radioactive isotopes of light elements, as well as for irradiation studies of reactor materials.[177]

SM-3 has a compact core consisting of 32 fuel assemblies and a metal beryllium reflector in a steel vessel. The core is loaded with three types of fuel assemblies containing fuel rods with a cruciform cross-section. The fuel meat is 90% uranium dioxide dispersed in a copper-beryllium-bronze matrix. Fuel assemblies consist of 188, 160 and

158 fuel rods and contain 1.128 kg , 0.96 kg and 0.948 kg of uranium-235, respectively. The amount of uranium-235 in the reactor core is therefore about 36 kg.[178] The average annual fuel requirement is 70 fuel assemblies containing about 79 kg of uranium-235.[179]

The utilization factor of the reactor is about 0.7. Its design service life is 25 years, which lasts until 2017. Technical upgrades of various reactor systems, however, may allow operation beyond that date.

Work is continuing to allow long-term irradiation of large samples of reactor materials. For this purpose, the uranium-235 content of the fuel rods was increased from 5 to 6 grams/cc. Work to replace the reactor core is reported to be underway.[180]

Russian research reactor experts believe that the SM-3 cannot be converted to LEU fuel and still maintain its key operating characteristics.[181]

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 for neutron-irradiation of materials, in order to investigate changes in their properties, as well as for the production of radionuclides. The reactors are used for research that does not require high neutron fluence, but does require that the neutron flux remains stable.

The RBT-6 reactor has a thermal power of 6 MW and its core consists of 56 irradiated fuel assemblies from the SM-3 reactor. The average burnup of the uranium-235 in its fuel assemblies is more than 35% when they are loaded and 50% when they are discharged. The total mass of uranium-235 in the reactor core at the beginning of a campaign is 32–34 kg.[182] The average duration of a campaign is about 40 days.

The RBT-10/2 reactor has a power rating of 7 MWt and is fueled with 78 irradiated fuel assemblies from the SM-3 reactor. The burnup of the fuel assemblies is 10–30% when loaded and averages 37–39% when discharged. The total mass of uranium-235 in the core at the beginning of the irradiation campaign is about 44–46 kg and the duration of each campaign is 60 days.[183] Its utilization factor is 0.6–0.7.

It was assumed that the RBT-6 would be retired in 2009 and the RBT-10/2 in 2012, but the results of assessments carried out from 2007–2011 led to the decision to prolong their operation until the end of 2020.

According to Russian experts, converting these reactors to LEU fuel is impossible because of their use of irradiated fuel of the SM-3 reactor.[184] However, since both reactors can also operate with fresh fuel and the design of their 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, the conversion of the RBT-6 and RBT-10/2 to LEU fuel would not appear to be necessary since they would be shut down when SM-3 is decommissioned.

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

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

The reactor core is assembled from hexagonal beryllium blocks and 48 to 58 fuel assemblies in a water pool. Each fuel assembly consists of 4 coaxial annular fuel cylinders with an active height of 1 meter. The fuel meat is composed of 90% uranium dioxide dispersed in an aluminum matrix. A fresh fuel assembly contains 356 grams of uranium-235, and the total mass of uranium-235 in a fully loaded core is 20.6 kg.[185] The average burnup of the discharged fuel is 55–60%. The utilization factor in recent years was about 0.6 and the annual HEU consumption is up to 39 kg.[186]

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 the modernization of reactor systems and equipment without long interruptions in operations, enabling an annual reactor utilization factor of about 60% during the upgrades.[187]

The possibility of converting MIR.M1 to LEU fuel was considered as part of the 2010 U.S.-Russian agreement. Preliminary analysis showed that conversion was possible with the development of a six-tube coaxial fuel assembly with 19.7% enriched uranium dioxide dispersed in an aluminum matrix, or uranium-molybdenum alloy containing 9% molybdenum (U-9Mo) particles dispersed in aluminum matrix.[188]

VVR-M: Petersburg Nuclear Physics Institute, Gatchina

The VVR-M is a pool-type, water-cooled reactor with a thermal power of 18 MW that was commissioned at the end of 1959. It has been used for studies in nuclear physics, the physics of condensed matter, materials science, radiobiology, and medical and industrial isotope production. During its lifetime, the reactor's systems have been continuously modernized.

The reactor core has a beryllium reflector and contains 145 VVR-M5 fuel assemblies. The fuel composition is 90% enriched uranium dioxide dispersed in an aluminum matrix. Each fuel assembly contains 74 g of uranium and the total uranium mass in the reactor core is 10.73 kg.[189] The reactor operates in a powered mode for up to 3,000 hours per year.[190] The duration of a single working cycle is 35 days, during which the reactor operates at 18 MWt power for 21 days. The burnup of the discharged fuel is 29%. Uranium-235 consumption during the ten annual working cycles is 13 kg.

The reactor can also use VVR-M5 fuel assemblies with 36% HEU.[191] The production of fuel with an enrichment of 19.7% would require a uranium density of 8.5 g/cm^3 in the fuel meat, which is not yet available.[192] 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 was brought to criticality in 2011. Powered start-up, scheduled for 2014, has been delayed, however.[193] The reactor is designed to conduct research in the field of nuclear physics, the physics of weak interactions, condensed matter physics, structural and radiation biology and biophysics, radiation physics and chemistry, and applied engineering.

The reactor core consists of 18 fuel assemblies of different compositions and shapes in a heavy-water reflector.[194] Twelve fuel assemblies containing 241 fuel rods with cruciform shape have irregular hexagonal cross-sections. Six square fuel assemblies contain 161 fuel elements each. The PIK reactor uses fuel rods of the SM reactor design with the length increased to 50 cm. The fuel composition is 90% enriched uranium dioxide dispersed in a copper-beryllium matrix. The 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 to be 27.5 kg.[195] Assuming that the PIK reactor operates 250 days per year with an average burn-up of the discharged fuel of 30%, its annual consumption of uranium-235 will be 83 kg.

Given its unique fuel and the fact that the process of commissioning has finally begun, the prospect of conversion of this reactor to LEU fuel in near future appears unlikely.

IR-8: National Research Centre Kurchatov Institute, Moscow

IR-8 is an 8 MWt pool-type reactor with a neutron reflector assembled from beryllium blocks that 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, tests candidate fuel materials for proposed nuclear power reactors, and produces radioisotopes.

The IR-8 reactor core consists of sixteen six-tube and four-tube fuel assemblies with a square cross-section. Uranium-molybdenum alloy dispersed in aluminum is used as fuel meat. The mass of 90% 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%.[196] A single working cycle is 41.7 days and 250 MWt-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 under the 2010 U.S.-Russian agreement. The conversion parameters were defined mainly by the possibility of maintaining the neutron flux at the level of 10^{14} $n/(cm^2 sec)$ without a substantial increase in power. Initial studies did not exclude the possibility of operating this reactor with uranium-molybdenum dispersion fuel enriched to 19.7%.

Argus: National Research Centre Kurchatov Institute, Moscow

The water-cooled and water-moderated Argus solution reactor has a thermal power of 20 kWt 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% and the total mass of uranium in the solution is 1.71 kg.[197] During 2006–2010 the reactor operated less than 10% of the time.[198]

The Argus reactor was on the list of six research reactors for which a preliminary study on conversion was carried out in accordance with the 2010 U.S.-Russia agreement. Its conversion to low-enriched fuel was completed in July 2014.

OR: National Research Centre Kurchatov Institute, Moscow

The water-moderated pool type OR reactor, with a thermal power of 300 kW, was designed for fundamental scientific and applied studies on radiation protection and radiation resistance of equipment. The reactor core contains 25 S-36 rod-type fuel assemblies, the uranium is enriched to 36% and the total uranium mass in the reactor core is 3.8 kg.[199]

The annual uranium-235 consumption is estimated to be 0.08 kg for 2,000 hours of powered operation per year. The OR reactor is also on the list of six reactors studied for possible conversion. A preliminary study concluded that reactor conversion is technically feasible with rod-type LEU fuel, but it would require the production and testing of either uranium-molybdenum dispersion or UO_2 dispersion fuel.

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 naval-propulsion reactors and to produce short-lived isotopes.

The reactor core consists of 40 liters of an aqueous solution of uranyl-sulfate (UO_2SO_4). The uranium is enriched to 90%; the mass of uranium-235 is equal to 3.2 kg.[200] For the period 2006–2010, Gidra operated less than 10% of the time. The Federal Program "Nuclear and Radiation Safety in 2008 and through 2015" called for its decommissioning.[201]

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

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

The reactor core is formed from 42 hexagonal tubular assemblies. The fuel meat is 90% enriched uranium dioxide dispersed in aluminum. The total mass of uranium-235 in the core is 6.76 kg.[202] The utilization factor has reached 85%. Assuming that the discharged fuel burnup is 45%, the estimated annual consumption of uranium-235 is 9.6 kg.

An initial study of conversion to LEU fuel has shown that the use of dispersion fuel with 19.7% enriched uranium and a density of 6.5 g/cm^3 would not lead to a reduction of the reactor's utility. It has not yet been determined, however, that this kind of fuel can be produced at a reasonable cost. This along with the fact that the reactor may be decommissioned in 10–12 years and coupled with the long lead time for developing and testing new fuel assemblies makes the value of converting the reactor unclear.

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

VVR-Ts is a heterogeneous, water pool-type reactor with a power of 15 MWt. It is designed for a wide range of research activities in the field of radiation chemistry, materials research, and activation analysis. Since 1980, the reactor has been used to produce medical isotopes, for neutron doping of semiconductors, and for the radiation modification of minerals.

The reactor core contains 70 VVR-Ts fuel assemblies, which have either three or five concentric tubes with a hexagonal cross section. The fuel is 36% uranium dioxide dispersed in an aluminum matrix. The five-tube fuel assemblies contain 103 g of uranium-235 and the three-tube assemblies contain 89 g of uranium-235. The amount of uranium-235 in the reactor core is estimated to be 7.6 kg.[203] 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 Kazakhstan's VVR-K reactor, for which LEU fuel with an enrichment of 19.7% 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 up the possibility of conversion of the VVR-Ts. The reactor is also involved in the production of medical isotopes. Conversion of the targets to LEU began in 2013.[204]

IRT-T: Tomsk Polytechnic Institute, Tomsk

The IRT-T is a water pool-type reactor with a power of 6 MWt. 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 most of the funding necessary for its normal operation. Since its launch in 1967, the reactor has undergone several upgrades. Its initial power of 2 MWt was increased to 6 MWt and the reactor's life was extended to 2034. Plans exist to increase the reactor power to 12 MWt.

Initially the core was loaded with EK-10 fuel assemblies with 10% enrichment. After the reconstruction of the core in 1971, it was modified to use IRT-2M fuel assemblies. Since 1979 the core has had a beryllium reflector and uses IRT-3M uranium-aluminum alloy fuel assemblies with 90% HEU. The core is formed of eight six-tube and twelve eight-tube IRT-3M fuel assemblies containing 309 g and 352 g of uranium-235 respectively. The total mass of uranium-235 in the core is 6.7 kg.[205] 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 findings are that the conversion to low-enriched uranium-molybdenum dispersion fuel would result in substantial hardening of the neutron spectrum, which would exclude its use for silicon doping.[206] As a result the operator is not interested in converting the reactor.

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

IRT-MEPhI is a 2.5 MWt pool 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 tubes and six assemblies with eight fuel tubes). The fuel is a uranium-aluminum alloy with 90% HEU. The total mass of uranium-235 in the core is from 3.5 to 5.2 kg.[207] The reactor operates at its nominal 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 some of the reactor capabilities would be diminished, it is possible to convert the reactor to IRT-4M fuel assemblies with 19.7% enrichment.[208] However, the reactor's operators believe that the use of IRT-3M fuel assemblies with U-9Mo dispersed in aluminum is more promising.[209] In any case, conversion will require the refurbishment of the reactor, which was scheduled as part of the Russian Federal Targeted Program "Nuclear and Radiation Safety 2008–2015." This work appears to be underway.

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

The 2 MWt IRV-M1 is a pool-type reactor that was constructed to conduct research on the radiation resistance of materials and electronic equipment. The design of the reflector and the experimental channels ensure a neutron flux with the hard spectrum needed to perform these tasks. The reactor was reconstructed after 1991 to increase its power to 4 MWt. The upgraded reactor is known as IRV-M2.[210] However, the reactor has not yet reached full capacity. It has a construction license that allows some operations, but the prospects for its eventual restart are unclear.[211]

The reactor core consists of 21 IRT-2M type fuel assemblies, which have three or four fuel tubes each. The fuel composition is UO_2 of 36% enrichment dispersed in aluminum. The mass of uranium-235 in a four-tube fuel assembly is 230 g, and 198 g in a three-tube assembly. The total weight of uranium-235 in the core is 4.5 kg.[212] Operating at nominal power for 2,000 hours per year, the consumption of HEU would be 0.83 kg.

4 Conversion of Soviet-origin research reactors outside Russia

Origins of the conversion program

The interest in the peaceful applications of nuclear energy that emerged in the 1950s was linked to the widespread belief that nuclear energy would be an essential element of technological progress and economic development. President Eisenhower's "Atoms for Peace" speech in 1953 marked the beginning of a process that eventually gave many countries access to nuclear materials, facilities, and expertise. The construction of research reactors was an integral part of this development. According to the IAEA, almost 300 research reactors in 48 countries were commissioned during the following decade.[213] Most of these reactors were supplied by the United States. The Soviet Union provided similar assistance to its allies, although its contribution to the expansion of the research reactor fleet abroad was smaller in scale. By the end of 1965, the Soviet Union had provided assistance with the construction of 14 research reactors in ten foreign countries: Bulgaria, China, Czechoslovakia, Egypt, the German Democratic Republic, Hungary, North Korea, Poland, Romania, and Yugoslavia. Figure 4.1 shows the evolution of the number of Soviet-built research reactors and critical assemblies outside Russia.

The research reactors that the Soviet Union built abroad were based on designs that were first deployed domestically. Accordingly, these reactors used the same type of fuel and the upgrades in Soviet domestic research reactors were followed by similar upgrades in their foreign counterparts. The early research reactors that were built in the 1950s usually used fuel with uranium enriched to 10% uranium-235, but, as fuel with higher enrichments were developed, reactors underwent modernization to take advantage of the new fuel. In a research reactor, the main performance criterion is the quantity of neutrons available for experiments or for the irradiation of targets used in isotope production. Since fuels based on highly enriched uranium (HEU) offer the most direct way to maximize neutron production from a given amount of fuel, most research reactors were eventually modified to use HEU fuel.

The cost or availability of HEU rarely played a significant role in decisions about modernization, since the cost of producing 90% HEU is only about 5% higher than that of uranium with an enrichment of only 20% and the quantities of uranium involved in the production of research reactor fuel were very small compared to other civilian uses of the material.[214] The only difference between domestic and exported reactors was the limit on the enrichment of uranium in fuel elements supplied abroad, as established by the Soviet Union. If a Soviet reactor used fuel with HEU enriched to 90%, fuel elements supplied to its foreign counterpart contained 80% HEU. However, due to the technological reserves of the fuel manufacturing process, the content of uranium-235 in 80% HEU fuel elements was kept the same, so this difference did not adversely affect performance of the reactors.

Although it is now understood that the use of HEU-based fuel in research reactors could present a significant risk from the point of view of nuclear proliferation and security, at the early stages of the Soviet program that helped build research reactors abroad priority was invariably given to reactor performance and to the needs of scientific research. Most of the Soviet-origin research reactors were converted to use fuel with HEU enriched to 36% and 80% as soon as the fuel became available.

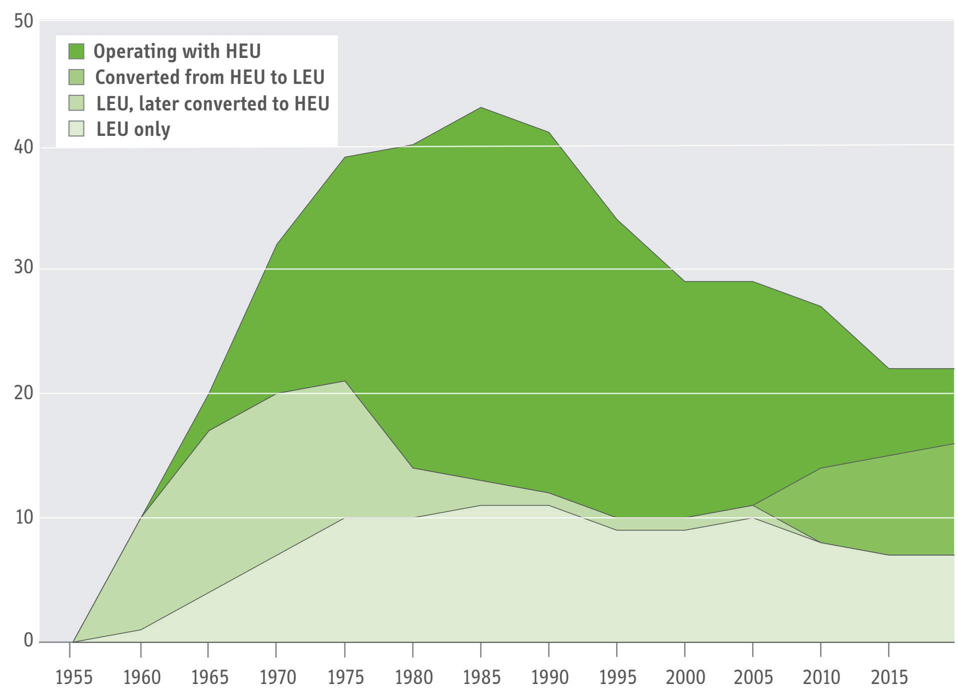

Figure 4.1. Soviet-origin research reactors and critical assemblies outside Russia.

The situation began to change in the 1970s, as part of a worldwide reassessment of the proliferation potential of civilian nuclear technologies, which followed the nuclear test conducted by India in 1974. In the late 1970s, the Soviet Union participated in the International Nuclear Fuel Cycle Evaluation (INFCE), conducted under the auspices of the IAEA. The study concluded that the proliferation resistance of the nuclear fuel cycle can be increased by reducing the enrichment of uranium in the nuclear fuel cycle, preferably to no more than 20% uranium-235, which was considered an adequate barrier to weapon usability.[215] The study also noted that research reactors were the main consumers of HEU in the civilian sector.

The Soviet Union took into account the recommendations of the INFCE study in its broader efforts to strengthen the nuclear nonproliferation regime. In particular, the Soviet government launched a program to reduce the enrichment of uranium used in research reactors. The first practical decision was taken in 1978, when Minsredmash (the Soviet Ministry of Medium Machine Building, a predecessor of Rosatom) banned supplying fuel with uranium enriched to more than 21% for reactors built with Soviet technical assistance that undergo modernization or are upgraded. The minister of Minsredmash was given the authority to allow export of fuel with higher enrichments, when such export was deemed necessary for uninterrupted operation of a reactor.

The decision to set the cutoff point for HEU exports at 21% of uranium-235 rather than 20%, as recommended by the INFCE study, most likely reflected the existing technological configuration of Soviet uranium enrichment plants, in which 21% enriched uranium was readily available. Also, Minsredmash experts apparently assumed that, from a practical perspective, uranium enriched to 21% uranium-235 is little different from 20% LEU in terms of weapon usability, even though in the IAEA safeguards context anything enriched to more than 20% is considered direct-use material.[216]

The limit on HEU fuel export was an important decision, since from then on, authorizations of HEU exports were subject to careful scrutiny and monitoring. But in other respects, the effect of the decision was rather limited. The ban did not directly affect the supply of HEU fuel for those reactors that had been upgraded already. Also, Minsredmash did not have suitable fuels that could replace HEU-based ones and did not have a program to develop these fuels. The only LEU fuel design that existed at the time was EK-10 fuel with 10% enriched uranium, which was used in a number of reactors in the 1950s and 1960s. But its production had ceased long before the 1970s and, in any event, the EK-10 design was so outdated that the Soviet Union never considered resuming its production. As a result, the Soviet Union continued to supply HEU fuel for existing reactors.

New reactors were also not affected by the 1978 export restrictions, since the restrictions covered only existing reactors built with Soviet technical assistance. At the time, the Soviet Union was building a new research reactor in Libya and was working on the modernization of a reactor in Vietnam. After internal Minsredmash deliberations, both reactors received HEU fuel—the IRT-2M 80% HEU fuel for Libya and the VVR-M2 36% HEU fuel for Vietnam. Later, IRT-2M fuel with 36% HEU was also supplied to the VR-1 Vrabec reactor in Czechoslovakia. This reactor was not covered by the ban since it was built by Czechoslovakia, even though it used Soviet-supplied fuel.

The impulse that helped the Soviet Union begin practical work on the conversion of research reactors came from the United States. In 1978, largely in response to the 1974 Indian nuclear test and the subsequent reevaluation of nuclear export policies reflected in the INFCE findings, the United States launched its Reduced Enrichment for Research and Test Reactors (RERTR) program. The goal of the program was to convert research reactors to LEU fuel. Although the Soviet Union was not involved in the program, the United States provided some documents, outlining the overall concept and some of its technical aspects, to senior Minsredmash officials. These documents were examined by Soviet experts and provided a starting point for a program to convert Soviet-designed research reactors to LEU fuel.

First steps toward conversion

The initial reaction of Soviet technical experts—designers, reactor operators, and scientists—to the RERTR documents provided by the United States was rather critical. Many of them expressed serious reservations about the goals of the program, arguing that the only relevant characteristic of a research reactor is its performance, and the level of the neutron flux in particular. Conversion was seen as an unnecessary interference with reactor operations. It should be noted that a number of technical experts in the West expressed similar objections to the program.

Nevertheless, the Minsredmash leadership insisted on launching a program that would explore the possibility of designing fuels with less than 20% enrichment that could be used in research reactors without major negative effects on their research outputs. Researchers were asked to present specific conversion proposals.

It should be underscored that, from the very beginning, the LEU fuel development program was focused on Soviet-designed reactors abroad. Conversion of reactors in the Soviet Union was never discussed, even though virtually all foreign reactors had Soviet prototypes and counterparts that used fuel of the same type.

At its early stages, the research program concentrated on neutron physics analyses of various pre- and post-conversion parameters of some of the research reactors. The results showed that, from the neutron physics point of view, in some cases a conversion to LEU fuel is indeed possible, although it would require development of new fuel with a higher concentration of uranium. That was seen as an entirely realistic task, since the technology available at the time allowed an increase in the density of uranium in the fuel meat. Also, there was room for increasing the thickness of the fuel meat by reducing the thickness of the cladding.

The approach to the conversion process adopted in the Soviet Union was very similar to that of the RERTR program, which is not surprising given the origins of the program. The conversion was expected to maintain a reactor's experimental performance (especially the neutron flux density in experimental channels) without significantly affecting its operational characteristics.[217] This resulted in the following key requirements:

- Conversion should not increase the core size or power of the reactor;
- Dimensions of fuel elements and assemblies should remain the same; the only variable parameter would be the thickness of the fuel meat;
- Excess reactivity of the core and fuel burnup should also remain unchanged; and
- The cost of the LEU fuel (with equivalent uranium-235 mass content) should be comparable to that of HEU fuel.

These principles were very similar to those of the RERTR program, although there were some differences. For example, RERTR framed its requirements in terms of the lifetime of fuel assemblies rather than reactivity of the core and fuel burnup.[218] In any event, the goals of the program were very ambitious, which largely explains why its implementation has been relatively slow. Another important factor is that the Soviet program gave very high priority to the interests and requirements of researchers, so the choice of conversion strategy required careful negotiations among all the parties involved.

The key technological approach to reactor conversion, which was adopted very early on and has been followed for many years now, was to increase the uranium density in the fuel meat. This was entirely consistent with the international approach to research reactor conversion. Another element of the fuel development strategy, which played a secondary role, was to increase the thickness of the fuel meat, with a corresponding reduction in the thickness of the cladding.

In 1982, the Soviet Union presented the principles of the program and the technical and economic approaches to conversion at a special conference of the Council for Mutual Economic Assistance (Comecon), attended by member states that were importing Soviet nuclear fuel for their research reactors. Since the presentation emphasized that conversion should preserve a reactor's performance, none of the operators registered objections to the program. In most cases, reactor conversion was a matter of a political agreement between governments, rather than a technical matter. Once the conversion started, operators would sometimes have to deal with a certain loss of performance, new licensing requirements, and the issues of cost, but these problems did not affect implementation of the program.

The fuel fabrication technology that was used in the Soviet Union to produce fuel for research reactors helped shape the general approach to LEU fuel design. Unlike the MTR plate-type fuel assemblies or TRIGA rod-type assemblies, fuel elements for Soviet-origin reactors have a tubular design and are fabricated by extrusion.[219] These fuel elements consist of triple-layer hollow tubes that contain fuel meat made of a uranium-aluminum alloy or uranium dioxide dispersed in an aluminum matrix. The cladding of these fuel elements is made of an aluminum alloy, and the cross-section of the tubes themselves can be round, square, or hexagonal.

At the time when the work on the conversion program began, the Soviet Union was exporting three main types of research reactor fuel assemblies with tubular fuel elements—IRT-2M, VVR-M2, and MR. It also supplied small batches of S-36 fuel cassettes with rod-type fuel elements that contained 36% HEU. Table 4.1 shows the main fuel assembly types that were used in Soviet-origin research reactors. As part of the conversion program, the industry developed modifications of each type of fuel assembly, with different sizes for fuel elements and with different enrichments. Original IRT-2M and MR fuel assemblies used 80% HEU; VVR-M2 assemblies contained 36% HEU. These assemblies used uranium-aluminum alloy in the fuel meat, but in the early 1980s the industry began a transition to a new composition based on uranium dioxide in an aluminum matrix. The new material allowed for a higher uranium concentration in the fuel meat. In some cases, this was insufficient—calculations showed that in order to achieve the conversion goals, fuel assemblies with thin fuel elements (less than 1.5 mm) would have to be based on a material with a uranium density that is higher than that in fuels based on uranium dioxide. The material composition considered as a substitute for uranium dioxide was uranium silicide or disilicide in an aluminum matrix (these options have been explored in the West as well).

Fuel assemblies type	Enrichment	Reactors
IRT (IRT-2M, IRT-3M)	36%, 80%, 90%	IRT-M, Belarus LVR-15, Czech Republic VR-1, Czech Republic SR-0, Czech Republic IRT-DPRK, DPRK IRT-M, Georgia IRT-5000, Iraq IRT-M, Latvia RKS-25, Latvia IRT-1, Libya VVR-SM, Uzbekistan
VVR-M (VVR-M2, VVR-M5, VVR-K)	36%, 90% (only in Ukraine)	RFR, Germany ZLFR, Germany VVR-SZM, Hungary VVR-K, Kazakhstan Ewa, Poland Maryla, Poland VVR-M, Ukraine DNRR, Vietnam
S-36	36%	IRT-2000, Bulgaria VVR-S, Romania IR-100, Ukraine VVR-SM, Uzbekistan
TVR-S	80%	R-A, Serbia R-B, Serbia
MR	36%, 80%	Maria, Poland Agata, Poland
Other HEU fuel		Anna, Poland RAKE, Germany Pamir, Belarus Kristall, Belarus Yalina-B, Belarus IVG.1M, Kazakhstan RA, Kazakhstan IGR, Kazakhstan Foton, Uzbekistan

Table 4.1. HEU fuel assembly types used in Soviet-origin research facilities outside Russia.

First results of the conversion research indicated that reactors with medium performance characteristics could be converted with fuel based on uranium dioxide in an aluminum matrix. Fuel modifications included an increased concentration of uranium in the fuel meat and a small increase in the thickness of the fuel meat. It also became clear that reducing the enrichment from 80 to 21% in one step would be extremely challenging, as it would require dramatic technological innovation. As a result, the program was structured to include two phases:

- Phase 1 would include reducing enrichment in IRT-M and MR fuel assemblies from 80% to 36%. This conversion would end all export of fuel with enrichment higher than 36%.
- Phase 2 would comprise the transition from 36% HEU fuel to fuel with an enrichment of 21% for all exported fuel.

Soviet engineers believed that the reduction of enrichment from 80% to 36% could be done with uranium dioxide-based fuel; further reduction, to 21%, would require the use of a different fuel composition. Uranium silicide and disilicide were regarded as candidates.[220] The decision to carry out conversion in two phases was also influenced by the original path taken by the RERTR program, which allowed for the two-step reduction of enrichment—first, from 93% to 45% and then from 45% to the LEU level.

While outlining plans for conversion of research reactors abroad, the Soviet Union confirmed its earlier decision not to convert its own research reactors. Most of these were high-flux reactors and it was believed that achieving neutron flux densities on the order of 10^{15} neutrons/(cm^2 sec) would require a uranium-235 concentration in the reactor core that could not be achieved with LEU fuels.

Once the decision to proceed in two phases was made, Soviet engineers were able to quickly develop 36% HEU fuels for IRT and MR reactors, as these relied on proven technology and did not require significant modification of the manufacturing process. In 1987 the Soviet Union began exporting 36% HEU-based fuel for IRT reactors and stopped exports of fuel with higher enrichments. Shortly thereafter the Soviet Union began exporting MR-type fuel with 36% HEU.

While the transition to 36% HEU fuel was a significant achievement, it also had the effect of reducing the urgency of the entire conversion program. In addition, first experiments with uranium silicide fuels proved disappointing, further slowing the program down. The deterioration of the Soviet economy in the late 1980s also took its toll by creating an environment in which conversion of research reactors was no longer seen as a priority. As a result, the practical work on reactor conversion effectively stopped. Russian scientists continued their work on neutron physics aspects of conversion, however, and on the development of LEU fuels, preserving the expertise that would be vital for future conversion projects.

The breakup of the Soviet Union in 1991 exacerbated the existing problems and added new ones as several former Soviet reputblics that hosted research reactors on their territory—Latvia, Belarus, Ukraine, Georgia, Uzbekistan, and Kazakhstan—became independent countries. In the Soviet Union, research reactors used HEU fuel, normally with 90% enrichment, but after 1991 these newly independent states became ineligible to receive HEU fuel. Since the future of the research facilities outside Russia was uncertain, some states—Latvia, Belarus and Georgia in particular—shut down their research reactors even before the Soviet Union broke up and moved to decommission them shortly after that. But some facilities remained in operation and all reactors had significant amounts of spent and fresh HEU fuel on site. Albeit not directly related to reactor conversion, it was a serious problem that required attention and complicated the conversion efforts.

International cooperation

For more than ten years the Soviet reactor conversion program was implemented independently from the RERTR program. However, closer cooperation between the programs was just a matter of time. The first step toward cooperation was made in 1993, when a delegation that included representatives from the U.S. Department of Energy and Argonne National Laboratory made a visit to Russia. As U.S. and Russian experts exchanged information on research reactors and reactor fuel, they discovered that despite the availability of numerous research publications in the area, much of the fuel-related information was new to both sides. U.S. experts also visited some of the leading Russian facilities involved in the conversion program.

The visit paved the way for close cooperation on reactor conversion between Russia and the United States. Russian scientists began to take part in the annual RERTR meetings, where they presented the results of their own conversion efforts.[221] They have also been actively involved in the European Nuclear Society's Research Reactor Fuel Management (RRFM) conferences since the first conference, held in 1997. As a result of this engagement, technological decisions made by Russian scientists and engineers have been subjected to discussions and peer review during conferences and bilateral events. International cooperation also helped foster a better understanding of a number of problems associated with reactor conversion. Joint U.S.-Russian projects that modeled neutronic and thermal-hydraulic parameters of nuclear reactors were particularly important.

Overall, thanks to this international cooperation, the Russian conversion program got a second wind that helped revitalize the efforts that began in the 1980s. Direct financial assistance provided by the U.S. Department of Energy to the Russian institutions involved in the conversion work was also an important factor in supporting the reactor conversion program and securing Russian governmental funding for the effort. The U.S. assistance was provided via Argonne National Laboratory, which would sign direct contracts with its partners in Russia.

The reactor conversion program was also discussed at high-level intergovernmental meetings. During several meetings of the U.S.-Russian Joint Commission for Economic and Technological Cooperation (the Gore-Chernomyrdin Commission) the two countries reiterated their commitment to cooperation in reducing the uranium enrichment of research reactor fuel. During the June 1994 Commission meeting, the head of Russia's Ministry of Atomic Energy (Minatom) Victor Mikhailov and U.S. Secretary of Energy Hazel R. O'Leary agreed to cooperate on the conversion of research reactors that use Russian fuel. The two parties also agreed to discuss the removal of spent HEU fuel from research reactor facilities back to its country of origin. In September 1994, representatives of the U.S. Department of Energy and the Russian Ministry of Atomic Energy signed a protocol of intent on cooperation in the development of higher-density 19.75% enriched uranium fuels, and on demonstrating the feasibility of conversion of specific reactors to LEU. This cooperative work started in 1996 with the goal of converting Soviet-origin research reactors outside Russia to 19.75% LEU fuel—slightly lower than the 21% enrichment threshold in the early Soviet program.

The first practical efforts of the new program were concentrated on the development of LEU VVR-M2 fuel assemblies, which at the time contained 36% HEU. Fuel elements of these assemblies were relatively thick (2.5 mm), leaving room for increasing the thickness of the fuel element meat. Modeling showed that the required conversion results could be achieved by increasing the uranium density in the fuel meat to about 2.5g/cm^3, which was possible with the uranium dioxide-based material that had already been used in some of the fuel assemblies.[223] The development and certification of the new fuel assemblies was completed in 2001.[224] All VVR-M2 fuel assemblies Russia has exported since then have been LEU-based.

Conversion of IRT-M fuel was a more challenging task, even though Soviet engineers had already developed an IRT-3M assembly that contained 36% HEU. The problem was that the IRT-M fuel elements were only 1.4 mm thick, so there was much less room for increasing the uranium load of the entire assembly by increasing the thickness of the fuel meat.

One possibility that was considered at the early stages of the program was a transition to uranium silicide to provide a higher uranium density. However, manufacturing silicide-based fuel was still an unproven technology that would require substantial investment in new fuel fabrication lines. Given that fuel fabricators were expected to continue production of uranium-dioxide fuels for Russian reactors, the investment in a parallel fuel production process was difficult to justify. Eventually, the issue was resolved when it turned out that uranium-silicide fuels, which were developed as part of the RERTR program in the mid-1990s, are not suitable for reprocessing (or, rather, could not be reprocessed at a reasonable cost). Since this would significantly limit the spent fuel management options available to operators and fuel suppliers, the uranium-silicide option was abandoned.

Instead, Russian engineers focused on improving uranium dioxide-based fuel for IRT-type reactors. Unfortunately, even with the highest concentrations of uranium in the fuel meat that could be achieved at the time, the uranium load of modified IRT-3M fuel assemblies still remained insufficient. As a result, the new fuel assembly developed for converted reactors, IRT-4M, used somewhat thicker—1.6 mm instead of 1.4 mm—fuel elements that allowed for thicker fuel meat. The density of uranium in the fuel assembly still remained somewhat below the necessary level, but IRT-4M fuel assemblies have been successfully used to convert reactors to LEU and, together with VVR-M2 assemblies, account for most of Russia's LEU-fuel exports today.

One of the Soviet-designed reactors, VVR-K in Kazakhstan, used fuel assemblies that had not been used in reactors outside of the Soviet Union. The development of an LEU fuel for it, known as VVR-KN, therefore was not completed until 2012.[225] Like the old 36% HEU VVR-K fuel, the LEU VVR-KN fuel was based on uranium dioxide in an aluminum matrix. However, because of its superior design, the new fuel helped improve the reactor performance after conversion. It was an important achievement of the program, as it demonstrated that conversion could be done without negatively affecting the reactor performance.

As uranium-dioxide fuels approached the limit of their performance and silicide-based fuel proved impractical because of the difficulty of reprocessing, the RERTR program began to concentrate on fuels based on uranium-molybdenum alloy. Early fuels of this type were based on U-Mo alloy dispersed in an aluminum matrix. Later, the development shifted to monolithic fuels. As part of its cooperation with RERTR, Russia became involved in the effort to develop high-density dispersion uranium-molybdenum fuels at the early stages of the program. Its contribution used the Soviet experience with fuels of this type—the AM-1 reactor of the first nuclear power plant in Obninsk, built in 1954, used uranium-molybdenum fuel. The development program has made substantial progress and certification of the new fuel is expected in the next few years.

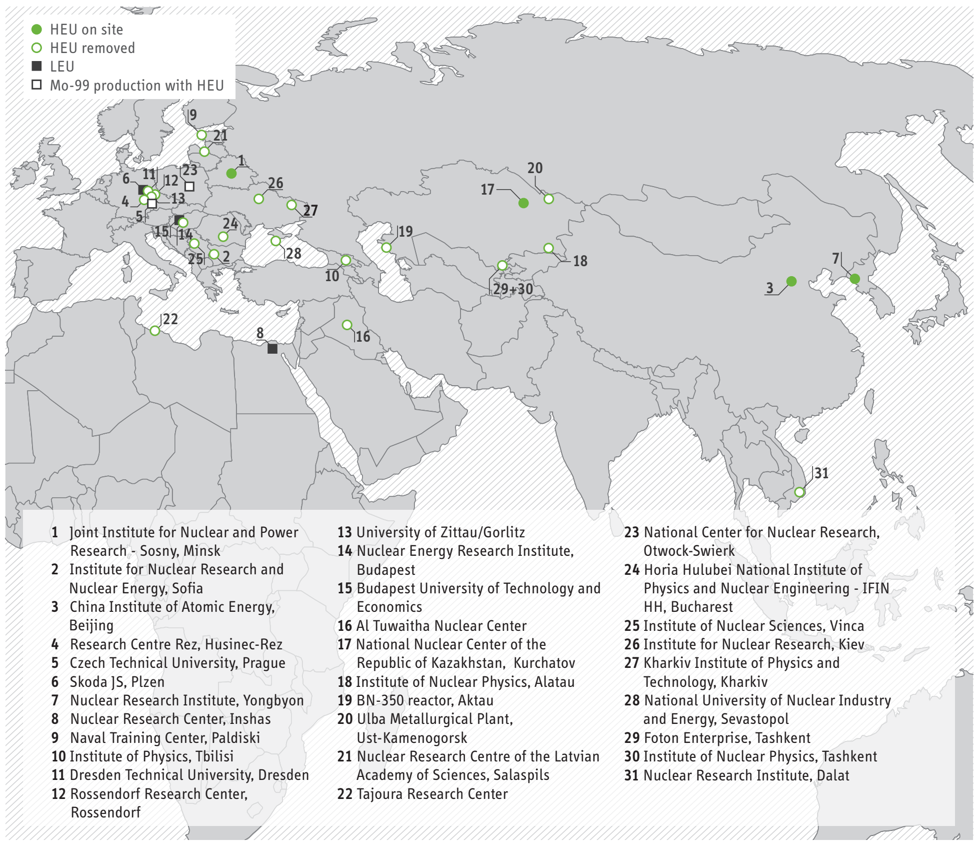

Figure 4.2. Soviet-origin reactors outside Russia.

By the end of 2016, all but three Soviet-origin research reactors outside Russia had been either shut down or converted to LEU (see Figure 4.2). Accordingly, Russia discontinued export of HEU fuel to Soviet-origin research reactors (even though, as Figure 4.3 illustrates, some HEU export continued).

The only reactor outside of the former Soviet Union that has not been converted to LEU is the IRT research reactor in North Korea. The reactor was built with Soviet assistance in the 1960s and used Soviet-supplied HEU fuel. The fuel supply was discontinued at the time of the breakup of the Soviet Union, so it is possible that the reactor has been shut down. However, there is no reliable information about the current status of the reactor or its fuel.

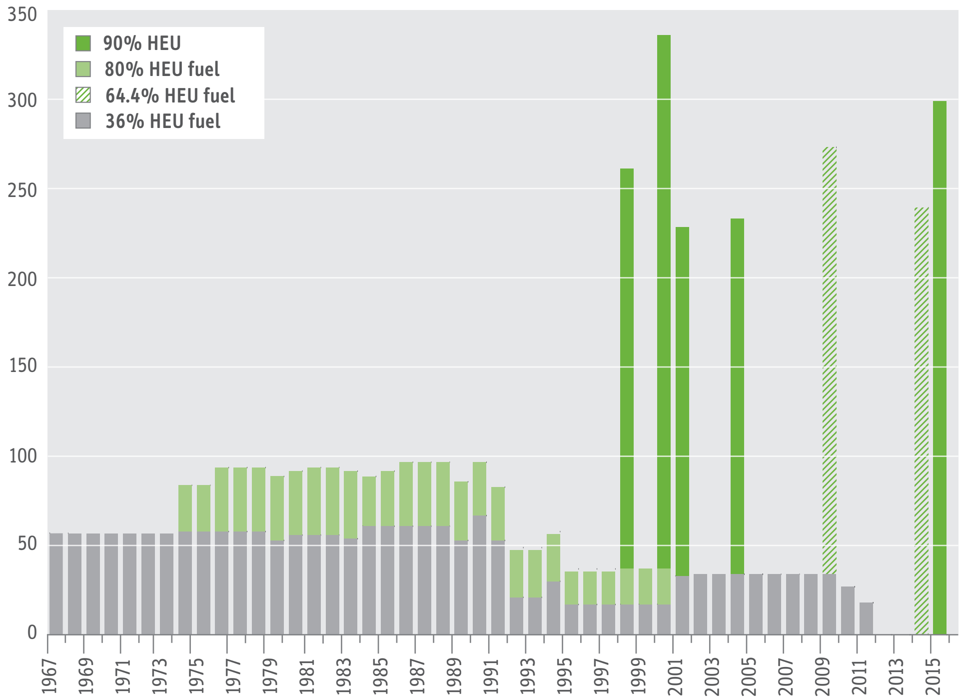

Figure 4.3. Estimate of HEU exports from Russia to countries outside of the Soviet Union (kg of HEU).[226]

The two reactors in the former Soviet Union still operating with HEU fuel are in Kazakhstan. These reactors, IGR and IVG, use a rather exotic type of fuel, so developing LEU fuels for them could take time. However, Russia, Kazakhstan and the United States are working on conversion of the IVG reactor—in 2014 LEU fuel developed in Russia was undergoing reactor tests.[227]

Conversion and removal of spent nuclear fuel

The fuel supply arrangements that were made by the Soviet Union as it was helping build research reactors abroad did not contain provisions for removal of spent fuel. Accordingly, virtually all research reactors outside of Russia accumulated significant amounts of spent fuel on site, including fuel that contained HEU. Some spent fuel from research reactors in the former Soviet republics has been removed for reprocessing, but neither the Soviet Union nor Russia had a consistent program for managing spent fuel from research reactors, whether inside the country or abroad.

When Russia and its international partners began working on conversion of Soviet-origin research reactors and repatriation of HEU, they recognized that this work should eventually address spent HEU fuel as well. From a nuclear security point of view, the risks associated with spent fuel from research reactors is comparable to that of fresh fuel, as spent fuel is normally not sufficiently self-protected by the gamma field produced by the fission products it contains. The issue of spent fuel added new complexity to the material repatriation program, as Russia had no experience in taking back spent fuel from research reactors abroad. Theoretically, the countries that hosted research reactors could dispose of spent fuel in their own territory (e.g., in a geologic repository), but this option was rejected at the early stages of the program, largely because in most cases spent fuel of these reactors still contains substantial amounts of HEU. This meant that return to Russia as the only viable choice. Russian law, however, directly prohibited this kind of take-back, which it considered an export of radioactive waste, initially restricting any activity in this area. In 2001 the law was changed, however, to allow the return of foreign spent fuel to Russia for reprocessing, which opened a way for practical work on repatriation of spent fuel from Soviet-origin research reactors.[228]

The beginning of practical efforts to remove Soviet-origin spent nuclear fuel was greatly facilitated by the fact that, in 1996, the United States adopted its own program of removing U.S.-origin spent fuel from foreign research reactor facilities. In 1999, Russia, the United States and the IAEA began trilateral discussion that eventually established the Russian Research Reactor Fuel Return (RRRFR) program, largely modeled after the U.S. Foreign Research Reactor Spent Nuclear Fuel Acceptance program, to manage repatriation of fresh and spent HEU from Soviet-origin research reactors. In October 2000, the Director General of the IAEA sent a formal letter to 16 countries with Russian-origin nuclear fuel used in eligible research reactors and research facilities, inviting them to participate in the program (no letter was sent to North Korea). All invited countries that had Soviet-origin HEU fuel eventually joined the program.[229]

The first shipment of excess fresh HEU fuel sent to Russia under the RRRFR program occurred in 2002, when Russia accepted unused fuel from the Vinca nuclear research center in Belgrade. The first shipment of *spent* fuel did not take place until 2006, when the program removed spent fuel from the VVR-SM reactor in Uzbekistan. This also was the first shipment that took advantage of the provisions of the new Russian law adopted in 2001. HEU from repatriated fresh fuel is normally downblended to LEU. Spent fuel is sent for reprocessing. In virtually all cases, repatriation of fuel to Russia was integrated with the conversion of research reactors.

Throughout the program, the United States has provided significant financial aid and logistical assistance with program implementation. The entire effort is an impressive example of Russian-U.S. cooperation in the area of nonproliferation and nuclear security. Chapter 5 describes the program in more detail.

Conversion of Russian research reactors

The possibility of converting Russia's own research reactors was discussed at the early stages of the reactor-conversion efforts. Those discussions remained largely theoretical, however, even as work on conversion of reactors abroad was making steady progress. Many Russian experts rejected out of hand the possibility of converting Russia's reactors, arguing that conversion would be very expensive and would degrade the reactors' performance. Rosatom's leadership also did not see any political or economic justification for such a program.

This attitude toward conversion notwithstanding, a number of projects, most of them supported by foreign grants, looked into the possibility of converting some Russian research reactors or at least reducing the enrichment of their fuel. For example, researchers from the St. Petersburg Nuclear Physics Institute demonstrated that the PIK reactor, which was under construction at the time, could be converted to use 36% HEU in its fuel instead of the 90% HEU that the reactor would eventually use.[230] Other projects studied the possibility of converting additional Russian research reactors, such as the VVR-M, the IR-8, and others. None of these studies, however, resulted in practical conversion projects.

As the conversion of Soviet-origin reactors in foreign countries continued to make progress, however, it became increasingly clear that there would have to be a serious discussion of the conversion of Russia's own reactors as well. That understanding was helped by the positive experience of converting low, medium and even high-flux research reactors in other countries, such as the OSIRIS reactor in France. It showed that, from a technical point of view, conversion of low and medium-flux Russian reactors was entirely feasible, although it would require a certain amount of effort.

In addition, having worked for a long time on the development of LEU fuel for research reactors in foreign countries, Russian experts began to change their attitude toward the idea of converting Russia's own reactors. They gradually arrived at the realization that conversion was a feasible option and that, in many cases, it would not significantly affect reactor performance. The Russian government also became increasingly determined to make a more substantial contribution to the nonproliferation effort.

On 16 September, 2002, Russian Minister of Nuclear Energy Alexander Rumyantsev and U.S. Secretary of Energy Spencer Abraham made a joint statement that listed "work on accelerated development of LEU fuel for both Soviet-designed and United States-designed research reactors" as one of the most important areas where joint cooperation could lead to a reduction of HEU fuel use.[231] The issue was also addressed at the presidential level. At their 24 February, 2005 summit meeting in Bratislava, Presidents Vladimir Putin and George W. Bush made a joint statement on nuclear security cooperation, including that

> "The United States and Russia will continue to work jointly to develop low-enriched uranium fuel for use in any U.S.- and Russian-design research reactors in third countries now using high-enriched uranium fuel, and to return fresh and spent high-enriched uranium from U.S.- and Russian-design research reactors in third countries."[232]

Even though the statement did not specifically address the conversion of research reactors in Russia, the high-level declaration on the importance of conversion helped support efforts in that area.

Discussions on possible ways to implement a conversion program for Russian reactors continued for several years. Finally, on 7 December, 2010, the State Atomic Energy Corporation "Rosatom" and the U.S. Department of Energy signed an Implementing Agreement to jointly conduct conversion feasibility studies on six Russian HEU-fueled research reactors:[233]

- The IR-8, OR, and ARGUS reactors at the Kurchatov Institute;
- The IRT at the Moscow Engineering Physics Institute (MEPhI);
- The IRT-T at the Tomsk Polytechnic University; and
- MIR.M1 at the Scientific Research Institute of Atomic Reactors (NIIAR)

The U.S. Department of Energy provided financial assistance to support this research through contracts between the U.S. Argonne National Laboratory and individual research institutes in Russia. Since most of the practical work involved development of suitable LEU fuels, Rosatom institutes played a leading role on the Russian side of the program.

The reactors included in the program are very different in terms of the power level, core design, fuel, and operational characteristics. Accordingly, the feasibility studies had to consider a range of conversion options, taking into account the neutron physics and thermo-hydraulics parameters of the reactors pre- and post-conversion. The studies also explored the safety implications of conversion. Since the work was done in a collaborative effort, scientists were able to employ Russian as well as U.S. computer codes, which helped achieve high accuracy and reliability of the results. The calculations that have been completed so far as part of this project indicate that, in most cases, the conversion will require development of uranium-molybdenum dispersion fuels. It will also require developing technology that would allow safe transportation and processing of spent LEU fuel. One of the reactors included in the feasibility studies, Argus, is an aqueous homogeneous reactor, which does not require new fuel elements or assemblies. The conversion of this reactor began in 2013 and the reactor reached criticality with LEU fuel in July 2014.[234] It is the first conversion of a Russian domestic reactor and, although the power of this reactor is small—only 20 kW—it is a very important step in the conversion activity. The IRT reactor at MEPhI is expected to be converted as well.[235]

The future of the conversion program

Russia has been engaged in various reactor conversion projects for more than 30 years. The program was initially focused on limiting the export of Soviet and Russian HEU fuel abroad, but it has grown with time into a full-scale HEU minimization effort that supports the goals of the RERTR program and works in close cooperation with the international community. The Russian program would be impossible without constant attention and the support of the leadership of the country and of its nuclear industry, which played a key role in initiating and sustaining the program.

Reactor conversion has proved to be a challenging task, largely because of the ambitious goals set for the program right from the start—to preserve the reactors' performance after conversion. Most of these challenges have been successfully addressed and most Soviet-origin research reactors abroad have already been converted to LEU. The program is nearing completion as the few remaining reactors are expected to undergo conversion in the near future. The success of the Russian program was due, in large part, to the decision to rely on tried and tested technological solutions in fuel development. Fuels based on uranium dioxide in an aluminum matrix and the extrusion technology of fuel fabrication have proven competitive and capable of maintaining the performance of the converted reactors without significant changes. Indeed, in some cases reactor performance has actually improved.

International cooperation was another extremely important factor in the success of the conversion program. This cooperation was not limited to technical work as Russia worked with its international partners to provide political support of the conversion and fuel-repatriation programs. Close contacts between Russian and Western scientists also played an important role. If Russian scientists and engineers worked in almost complete isolation from their foreign colleagues during the early days of the program, today they are playing a major role in the broad international research reactor conversion effort. It has been widely recognized that the success of the program to convert Soviet-origin research reactors is an impressive example of successful international cooperation.

Since the program to convert Russian-designed reactors in other countries is nearing completion, the focus of the conversion effort can be shifted to reactors in Russia. The program is concentrated on the development of high-density fuels. The experience and expertise gained in the course of the conversion programs so far will definitely be extremely useful for the domestic conversion effort.

The program has demonstrated that the success of the HEU minimization effort critically depends on a comprehensive approach to the problem—from development of high-density fuels to solving the issues of repatriation of fresh and spent fuel. International cooperation is also vitally important as it creates the necessary momentum and provides opportunities for finding better solutions to the technical, organizational, and political problems involved in the complex issue of civilian HEU minimization.

5 Removal of Russian-origin HEU fuel from research reactors outside Russia

Introduction

During 1950–1980, the Soviet Union and the United States pursued large-scale programs to introduce developing nations to the civilian uses of nuclear energy including the production of medical and industrial isotopes. As a result, research reactors were built in several dozen countries. Most of these reactors used fuel that contained highly enriched uranium (HEU) with an enrichment of more than 90% in some cases.

The United States built 40 research reactors that used HEU-based fuel in foreign countries.[236] The Soviet Union eventually built or provided assistance with the design and fuel supply for 29 research reactors and other research facilities in 13 countries. About three quarters of these facilities used HEU fuel. A number of research reactors and other facilities were located on the Soviet territory outside Russia (see Chapter 4 for details). After many years of operation, large stockpiles of fresh and spent HEU fuel, with different enrichments, accumulated at these facilities.

In the 1970s, recognition of the nuclear proliferation potential of research reactors and associated technologies led the United States and the Soviet Union to initiate programs aimed at reducing the enrichment of fuel used in research reactors and repatriating the HEU fuel to their country of origin. The United States, working in partnership with the IAEA, launched a program to remove HEU fuel from U.S.-built research reactors in other countries and to convert these reactors to LEU fuel.[237] The Soviet Union initially focused its efforts on reducing the enrichment of the fuel for Soviet-designed reactors built abroad to a maximum of 36%. By the 1990s the Soviet Union had ended all exports of fuel enriched to more than 36%.

In the late 1990s, as part of a second stage of the program to reduce the enrichment of the fuel used in Soviet-designed reactors to 20%, Russia, the United States, and the IAEA launched a trilateral Russian Research Reactor Fuel Return program (RRRFR). This chapter focuses on cooperation between Russia and the United States in the implementation of this program.

Scope of the RRRFR program

After the break-up of the Soviet Union, 14 HEU research reactors and critical assemblies were left on the territory of six newly independent republics other than Russia.[238] In addition, at the time there were a total of 22 HEU-based fuel research reactors and critical assemblies built with Soviet assistance in 13 countries outside of the Soviet Union.[239]

All these countries had at least one Soviet-origin HEU facility, with the exception of Egypt and China.[240]

In 1999, Russia, the United States and the IAEA finalized a list of countries and research facilities that had received Soviet-made nuclear fuel. In October 2000 the relevant ministries and agencies of 16 countries on that list (Belarus, Bulgaria, China, the Czech Republic, Egypt, Germany, Hungary, Kazakhstan, Latvia, Lithuania, Poland, Romania, Serbia, Ukraine, Uzbekistan, and Vietnam) received a letter from IAEA Director General Mohamed ElBaradei asking them whether they would be interested in having their HEU-based fresh and spent nuclear fuel removed back to Russia.[241]

	HEU facilities	LEU facilities
	Countries outside of the Soviet Union	
Bulgaria	**IRT-Sofia**	
China		SPR IAE, HWRR
Czech Republic	**LVR-15, VR-1, SR-0**	LR-0
Egypt		ET-RR-1
Germany	**RFR, RRR, RAKE, ZLFR**	AKR
Hungary	**VVR-SZM**	ZR-6M, Training reactor
Iraq	IRT-5000	
Libya	**IRT-1, IRT CA**	
North Korea	IRT-DPRK	
Poland	**Maria, Anna, Agata, Maryla, Ewa**	
Romania	**VVR-S**	
Serbia	**R-A, R-B**	
Vietnam	**DNRR**	
Total	22 HEU **(20 covered by RRRFR Program)**	7 LEU
	Former Soviet states	
Belarus	**IRT-M, Pamir**	
Georgia	IRT-M, Breeder-1	
Kazakhstan	**IRG, IVG.1M,** RA, **VVR-K, FM VVR-K**	
Latvia	**IRT-1M, RKS-25**	
Ukraine	**VVR-M**	IR-100, IR-100 CA, Subcritical assembly
Uzbekistan	**VVR-SM, Foton**	
Total	14 HEU **(11 covered by RRRFR)**	3 LEU

Table 5.1. Soviet-built research reactors outside Russia and other nuclear installations and their coverage by the RRRFR program (marked in bold).

By the time Russia, the United States and the IAEA began discussions that established the RRRFR program, Soviet-origin nuclear material had already been removed from a number of countries and individual facilities. During 1991–1994, all fresh and spent nuclear fuel was removed from Iraq to Russia, in accordance with UN Security Council Resolution 687 (1991) and the subsequent UN resolutions that approved the plan developed by the IAEA. Fresh fuel for the Soviet-origin IRT-5000 reactor and for the

Tammuz-2 reactor supplied by France was brought to Russia in November 1991. Spent fuel was transferred to Russia in December 1993 and February 1994.[242] In 1998, fresh and spent HEU fuel was removed from the Institute of Physics in Tbilisi, Georgia. That project, known as Auburn Endeavor, was managed by the U.S. Department of Energy. Since Russia, Georgia and the United States could not agree on the terms of the removal of the fuel back to Russia, it was taken, with U.S. assistance, to the Dounreay nuclear complex in Scotland.[243] The experience of these projects demonstrated the need for a formal program to manage removal of Soviet-origin nuclear material.[244]

Russia also removed HEU material from some of the former Soviet states without outside assistance. In 1995, all nuclear material was removed from the naval center in Paldiski, Estonia, the site of two land-based submarine training reactors.[245] During 1997–1998, the fuel from the RA and IVG.1M research reactors in Kurchatov, Kazakhstan was shipped to Russia.[246]

The letters from the IAEA Director General that started the RRRFR program were sent to almost all countries that had potentially eligible nuclear material in 1999. An exception was made for North Korea, which had for years been blocking an IAEA investigation of the completeness and correctness of the DPRK's declaration of its nuclear activities under its Safeguards Agreement of 1992.[247]

Of the sixteen states that received the letters, thirteen gave their consent for the removal of HEU fuel to Russia, while Germany informed the IAEA that it would give its final answer after studying the proposed program in more detail. Egypt informed the Agency that all its nuclear fuel was LEU-based. China, which also did not have Soviet-origin HEU fuel, did not respond to the IAEA letter. Initially, the IAEA received no response from Libya. However, Libya joined the program in 2004, after it relinquished its WMD programs in a trilateral agreement with the United States and the United Kingdom.

The legal framework

The legal framework of the RRRFR program is built on four types of agreements between the parties that are involved in the removal of material:

- Between Russia and the United States,
- Between Russia and the country whose research reactor is involved,
- Between the United States and that country, and
- With countries along the nuclear material transfer route.

On 27 May, 2004, Russia and the United States signed a bilateral agreement establishing a legal framework for Russian-U.S. cooperation in the repatriation of Russian-origin research reactor fuel from the countries that responded positively to the IAEA letter.[248] The agreement was to remain in force for a 10-year period. In December 2013, as the original term was approaching its end, the two countries extended the agreement for another 10 years, until 27 May, 2024, through an exchange of diplomatic notes.

Implementation of the Agreement has been facilitated by support from the highest political levels in both Russia and the United States. For example, on 24 February, 2005, during the Russian-U.S. summit in Bratislava, Slovakia, presidents Putin and Bush signed a Joint Statement on Nuclear Security Cooperation that reiterated the two countries' commitment to continued cooperation in the removal of fresh and spent HEU fuel from the Russian and U.S.-designed research reactors in third countries.[249] At their summit meeting in July 2009 presidents Medvedev and Obama issued a Joint Statement on Nuclear Cooperation that reconfirmed their nations' commitment to cooperation in this area.[250]

To coordinate the implementation of the February 2005 Joint Statement, the two countries set up a bilateral Senior Interagency Working Group, led by Alexander Rumyantsev, head of Russia's Federal Agency on Atomic Energy (which subsequently became Rosatom) and U.S. Secretary of Energy Samuel Bodman. Responsibilities of the working group were later transferred to the new Nuclear Energy and Nuclear Security Working Group, set up under the umbrella of the U.S.-Russian Bilateral Presidential Commission. The working group was co-chaired by the Rosatom Director General, Sergey Kiriyenko, and then U.S. Deputy Secretary of Energy Daniel Poneman.

Legally, transfer of fresh and irradiated material had to be handled differently. Under Russian law, the import of fresh nuclear fuel requires only a foreign trading contract; no special intergovernmental agreements are necessary. Spent fuel import, however, was prohibited until 2001, when Russia implemented a number of legislative changes to allow take-back of Russian-origin spent fuel from both power and research reactors.[251]

The new law also set a number of conditions for fuel return. One of them was the requirement of an intergovernmental agreement to regulate the process. As a result, states participating in the RRRFR program have to sign separate bilateral agreements with Russia on cooperation in the removal of the research reactor fuel to Russia, and with the United States on U.S. Department of Energy financial and technical support.[252]

By the time the program was formally launched in 2004, Russia already had relevant agreements in place with the Czech Republic, Kazakhstan, Uzbekistan, and Ukraine. Similar agreements had to be negotiated with the other participating states. Russia has negotiated 12 and signed 11 intergovernmental agreements on cooperation in the removal of spentw nuclear fuel to Russia, including an updated agreement with Uzbekistan (see Table 5.2).

In some of the fuel removal projects, the land part of the route crossed the territory of third countries. In such cases, a multilateral intergovernmental agreement had to be signed on the transportation of nuclear material between the country of origin, Russia, and the transit state. For example, the removal of fuel from Bulgaria, Hungary and the Czech Republic was conducted via the territory of Ukraine; fuel from Latvia was removed via Belarus; from Serbia via Hungary and Slovenia, and from Uzbekistan via Kazakhstan. The nuclear fuel transit agreements were needed to formalize transportation arrangements and to resolve the issue of liability in the event of an accident. These transit agreements can cover the transit of nuclear power reactor fuel as well as research reactor spent fuel.

The terms and the procedures for each individual transport operation are set out in a separate document that is drawn up in accordance with the conditions of the transit agreement. Such separate documents are agreed upon by the parties involved, as an appendix to the main agreement, shortly before fuel removal.[253]

Country	Status as of 2017
Belarus	Signed on October 8, 2010
Bulgaria	Signed on January 18, 2008
Czech Republic	In place since 1994
Germany	Prepared in 2010, but not signed[254]
Hungary	Signed on July 22, 2008
Kazakhstan	In place since 1993
Latvia	Signed on December 3, 2007
Libya	Signed on October 21, 2009
Poland	Signed on September 1, 2009
Romania	Signed on February 19, 2009
Serbia	Signed on June 10, 2009
Ukraine	In place since 1993
Uzbekistan	Signed on May 15, 2012. Replaced the 1997 agreement.[255] Additional agreement signed on April 9, 2014.[256]
Vietnam	Signed on March 16, 2012 [257]

Table 5.2. Intergovernmental agreements on the removal of spent nuclear fuel to Russia.

Financial aspects of the program

Under the U.S.-Russian Agreement of May 27, 2004, the United States provides financial support for the fuel removal projects. The Agreement also allows the parties to seek "financial and technical support from [other] IAEA member states."[258] Under the terms of the document, Russia allows the import of fuel assemblies and nuclear materials on the condition that all the costs are covered by the United States or a third party. In most cases involving HEU fuel, all the costs of preparing the material for removal, obtaining transportation licenses, and handling the material on the Russian territory have been paid for by the U.S. Department of Energy.[259]

A country is eligible for assistance if it has at least one reactor of Russian design and has agreed to transfer its fuel to Russia. Also, the United States and Russia must agree that the fuel transfer "would advance the objectives of nuclear non-proliferation." The United States agrees to provide financial assistance for the transfer of fuel if the reactor is converted to LEU fuel or shut down. The conversion, however, is conditioned on the availability of properly licensed LEU fuel.[260] Under a separate program, with IAEA facilitation, the United States also provides financing for projects to convert research reactors to LEU fuel.

Under the terms of the intergovernmental agreement, Russia assumes responsibility for physical protection, control and accounting of the removed fuel in accordance with IAEA standards. It also pledges not to enrich the uranium contained in the removed fuel, nor to use that uranium in any military programs, and also not to export that fuel or any material obtained from it.

The total cost of the RRRFR program is estimated to be over $200 million and most of its efforts are to be completed by 2016.[261] As of January 2013 the payments to Russian subcontractors for the removal and processing of fuel, including preparatory work and delivery of fresh fuel, had reached about $150 million. It is expected that the U.S. government will spend a total of approximately $450 million on programs to repatriate both Russian and U.S. origin HEU fuel. This figure does not include additional financial assistance for complementary projects that are agreed upon separately, such as the U.S. assistance to Ukraine for the construction of a neutron source facility in Kharkov.[262]

A number of projects also involved financing by third parties or in-kind contributions by other governments. The removal of 48 kg of HEU from Serbia in 2002, for example, was co-financed with $5 million from the Nuclear Threat Initiative, a U.S. nonprofit organization. That operation also received financial support from the Czech Republic, European Union, IAEA, and Russia. The Czech Republic also contributed additional containers that were used to transport the material.

Difficulties in the implementation of the program

The Russian and U.S. entities implementing the RRRFR projects encountered a number of infrastructure, financial, and political difficulties, especially at the early stages of the program. By now, however, most of these difficulties have been successfully resolved.

Infrastructure limitations

When the RRRFR program began, Russia had only 16 special containers of the TUK-19 type suitable for spent nuclear fuel removal operations. Each of these containers can hold up to four irradiated fuel assemblies. This limited the scale of removal operations. Also, the TUK-19 containers were certified only for railway transportation.

In 2008, the Czech company *Skoda* was contracted to produce 6 VPVR/M containers, each of which could hold up to 36 fuel assemblies. This made possible an increase in the number of removal operations from four in 2006 to six or seven in each of

2009 and 2010. The new containers also reduced the RRRFR program's transportation costs.[263] Certification of the VPVR/M containers for compliance with Russian standards presented an additional challenge for the RRRFR program, as the Russian licensing standards are often different from those in Europe and the United States and the use of foreign-made containers for spent nuclear fuel transportation is not a common practice in Russia.[264]

The Czech fuel assembly containers were designed for transportation in universal ISO cargo containers, making it possible to transfer spent fuel not only by railway but also by sea and air.[265] To further enable such operations, Russian engineers designed and built a transportation package for the TUK-19 fuel containers. The new transportation package significantly expanded the options for the handling and transportation of Russian fuel containers by various modes of transport. The first RRRFR airlift of spent nuclear fuel, from Romania, was conducted in June 2009 using 16 Russian-made fuel containers housed within standard ISO containers.

Overall, the enlargement of the container fleet and the adaptation of containers for intermodal transportation gave the program added flexibility in the planning and execution of removal operations, increased the speed of the program's implementation and reduced transportation costs.

Financial difficulties

The financial difficulties encountered by the RRRFR program had two main causes. One was the high cost of some of the spent fuel removal operations (such as the removal of fuel from the Vinca Nuclear Research Institute in Serbia) due to the deterioration of fuel assemblies. The other was that the United States, the main donor of the program, does not finance the removal of research reactor fuel with enrichment below 20%, i.e., low-enriched fuel. That was why additional funding sources had to be sought for the removal of fresh and irradiated fuel from Serbia.

By the time preparations for the removal of fuel from Vinca began in 2005, irradiated fuel had already spent more than 20 years outside the reactor, and some of it was losing integrity and had deteriorated beyond acceptable conditions. Special procedures, as well as dedicated equipment, were required to handle the fuel and place it into containers.

Even though most of the costs of the removal projects are covered by the United States, under the terms of the RRRFR program the cost of the removal of radioactive waste into long-term storage in Russia has to be covered by the host country. Serbia could not afford to provide financing for the project. Therefore, that part of the operation required outside sources of funding. In the end, contributions were made by several international parties, including Russia, which provided $3 million toward the project costs.

The problems with financing added to the complexity of the project, which took more than five years to complete. At the same time, the Vinca project set an important precedent for operations that required outside financial support. Later, this experience was used to finance an additional flight of a transport aircraft to Libya to remove some of the spent fuel that remained there. Outside funding also financed the transfer of fuel from reactors not originally covered by the RRRFR program, such as the Foton reactor in Uzbekistan.

Political problems

The RRRFR program has run into various political problems over the years. Some have been resolved by political means and some by means of technology. Some have yet to be solved.

For example, the removal of spent nuclear fuel from Hungary in 2008 was delayed when Ukraine, believed to be acting for political reasons, was slow with the signing of the transit agreement. In the end, the United States and Russia found an alternative river transit route via Slovenia instead of the originally planned railway transit via Ukraine. This episode forced the RRRFR program to consider at least one backup route when preparing fuel removal operations.[266]

Another political problem arose in 2009 during the removal of spent nuclear fuel from the Tajoura Nuclear Research Center in Libya. All the diplomatic and technical issues related to the operation had been settled by the fall of 2009. In November 2009, five transport and packaging containers, delivered to Tajoura, were loaded with fuel and prepared for shipment. At the last moment, however, Libya's government declined to proceed with the transfer. The plane, therefore, had to return to Russia empty, leaving the containers with spent nuclear fuel in Libya. Permission to remove the material from the country was granted in late December 2009, after a month of intense diplomatic effort.[267]

Unresolved political problems still prevent the removal of fresh HEU fuel from Belarus and spent HEU fuel from Germany. German policy calls for sending nuclear fuel back to its country of origin whenever possible. In December 2006, 268 kg of Russian-origin HEU fresh fuel at the former East German Rossendorf nuclear facility near Dresden was repatriated to the Russian Federation. The RRRFR program was ready to remove the remaining spent fuel (around 190 kg with its original 36% enrichment) in 2010 and obtained the necessary approval from the German regulatory body.[268] However, at the last moment, Germany's Minister for Environment, Nature Protection and Reactor Safety refused to grant an export license for the material, due to the growing anti-nuclear sentiment in the country. That sentiment has increased the political risks of transporting spent nuclear fuel across German territory. For security and safety reasons, irradiated nuclear fuel containing HEU was moved to the Ahaus Intermediate Fuel Storage Facility, in North Rhine-Westphalia.[269] It is hard to say at the moment when the German government might be ready to reopen the issue of the return of this material to Russia.

Another example of political barriers hampering the removal of HEU fuel is Belarus. In October and November 2010, technicians removed fresh and spent HEU from the territory of the Joint Institute of Energy and Nuclear Research "Sosny" (JIENR). The fuel was left over from the Pamir mobile nuclear power reactor. In December 2010, Belarus announced that it would transfer all its remaining HEU to Russia.[270] In August 2011, however, in response to the economic sanctions imposed on it by the United States, Belarus suspended its participation in the RRRFR program.[271] Accordingly, the transfer of HEU, and a project to convert the associated critical assemblies to LEU, was put on hold. In 2013, however, most of the HEU fuel was moved to a storage facility in Belarus.[272]

Practical results

The priority for removal under the RRRFR program is fresh HEU fuel because it poses the greatest proliferation threat. The first RRRFR program fresh-fuel removal operation took place in August 2002, when some 48 kg of 80% HEU was removed from the Vinca Nuclear Research Institute in Serbia.[273] Transfers of irradiated HEU-based fuel under the RRRFR program began in January 2006, with the removal of spent fuel from the VVR-SM reactor at the Nuclear Physics Institute in Tashkent, Uzbekistan. As of May 2017, the most recent transfer took place in September 2016, when the last spent fuel of the Maria reactor in Poland was removed to Russia.[274]

Fresh HEU fuel removed to Russia is downblended and used in research or energy projects. Spent research reactor fuel is reprocessed at Rosatom's Mayak site in the Urals and the recovered HEU is blended with recovered uranium from spent light water (VVER) power-reactor fuel and turned into fresh material for power reactor fuel. Vitrified highly radioactive reprocessing waste is placed into long-term storage. If there is a relevant clause in the intergovernmental agreement then that waste could be returned to the country from which the spent fuel was removed, but this option has not been implemented in any of the shipments.

In the United States research reactor spent fuel return program, aluminum-based fuels are stored in a pool at the DOE's Savannah River Site and there is continuing discussion of the possibility of reprocessing and blend-down of the recovered HEU in the H-canyon reprocessing facility, which is still operable.[275] Zirconium-based spent research reactor fuel is stored at the DOE's Idaho National Laboratory for eventual disposal in a deep underground repository.[276]

As of May 2017, the RRRFR program had removed a total of about 800 kg of fresh HEU fuel and about 1,400 kg of irradiated HEU fuel in more than 60 operations (see Figure 5.1).

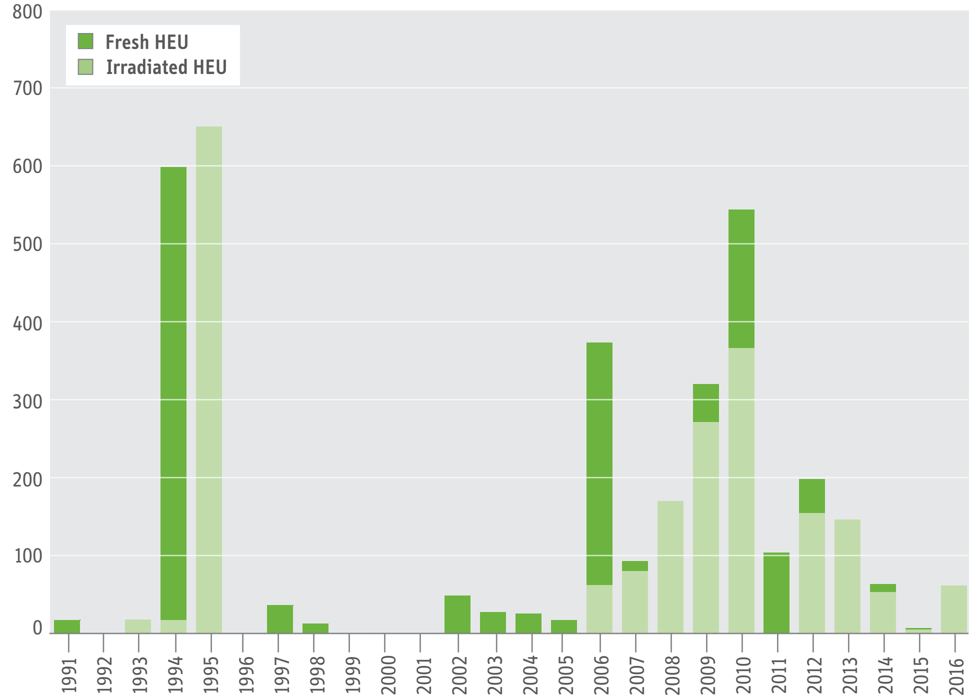

Figure 5.1. Return of Soviet-origin fresh and spent HEU fuel to Russia (kg of material).

All HEU fuel (both fresh and spent) has been completely removed from 11 out of the 14 states that participate in the RRRFR program, including Bulgaria, the Czech Republic, Hungary, Latvia, Libya, Poland, Romania, Serbia, Ukraine, Uzbekistan, and Vietnam.[277] Fresh HEU-based fuel has yet to be removed only from Belarus. There is also spent HEU fuel left in Germany and Kazakhstan. Kazakhstan has made a commitment to eliminate all its HEU.[278] The future of the Soviet-origin fuel in Germany is not clear.

There is general recognition, both in Russia and in the United States, that RRRFR is one of their most successful bilateral programs, not just in the area of nonproliferation, but also in Russian-U.S. cooperation as a whole.

Conclusion

Russian-U.S. cooperation under the RRRFR program has enabled the two countries to accumulate valuable expertise and experience of practical cooperation in the removal of sensitive nuclear materials from third countries. Various technical, financial and political problems that emerged during the program and required innovative diplomatic and logistical approaches have been successfully resolved (partially or completely).

Over the next two or three years the RRRFR will focus on the completion of projects to remove research reactor HEU fuel that still remains in Kazakhstan. The parties involved should also work to identify ways of overcoming the political obstacles that are preventing the removal of HEU fuel from Soviet-designed reactors in Belarus and Germany. Also, it should not be completely ruled out that North Korea might join the program at some point in the future. North Korean Foreign Ministry representatives say that the subject could be discussed in the context of a comprehensive settlement of the nuclear crisis on the Korean peninsula. North Korean diplomats have also expressed their interest in having the Soviet-built IRT-2000 reactor upgraded and its nuclear safety systems modernized.

Up until now the RRRFR program has focused solely on HEU fuel. LEU-based fuel was removed as part of RRRFR projects only when that fuel was being stored in inadequate conditions (Serbia) or when the host country was prepared to finance the LEU component of the fuel removal project (Romania). Russia and the United States, in cooperation with the IAEA, should consider the possibility of including LEU fuel in the scope of the RRRFR program. However, they should also identify sources of regular financing for these projects, especially since the frequency of operations to remove HEU fuel is going down, and the last operation of this kind will be completed in the next two or three years.

As part of the RRRFR program, the Russian parties involved have already created the infrastructure to remove irradiated research reactor fuel. In particular, they have built up a fleet of fuel containers required for such operations, as well as the loading equipment. All of that hardware could now be used to remove LEU fuel from research reactors. Containers built for the RRRFR program have already been used to remove LEU fuel from Romania.

Experience gained from the RRRFR program could also prove useful for future cooperation in the area of nuclear energy. For example, closer international cooperation could be pursued in the management of spent power-reactor fuel. The financial and legal arrangements, as well as the precise scope of such cooperation, would be different, but many of the coordination mechanisms and principles of cooperation tried and tested by Russia, the United States, and the IAEA would provide useful precedents.

6 Nuclear security aspects of HEU minimization

Introduction

The use of highly enriched uranium in various research facilities, such as research reactors or critical assemblies, is widely recognized as one of the most serious sources of the danger associated with a potential theft or loss of fissile material. Research facilities that use HEU are located at multiple sites around the world; many of them have HEU in quantities suitable for a nuclear explosive device, and they often lack adequate security protection. All this makes these facilities attractive targets for those looking to obtain nuclear material. The circulation of HEU that is required to maintain operation of the facilities that use HEU also presents a serious risk of the diversion or inadvertent loss of material.

It is understandable that the effort to reduce the danger associated with HEU has been focused on decreasing the number of vulnerable sites by removing the HEU and consolidating it in a limited number of highly secure locations. However, the consolidation program should be accompanied by a comprehensive effort to provide adequate security to the sites that contain attractive material. There are several reasons why this part of the HEU minimization program deserves at least the same level of attention as the removal of material. First, despite the impressive progress that has been made in recent years, complete HEU cleanout remains a distant goal. Civilian research facilities that use HEU (not to mention the facilities outside of the civilian domain) will remain operational for many years to come, requiring robust protection. Second, properly designed security arrangements should facilitate the HEU cleanout process by creating an appropriate cost and benefit structure that provides incentives for HEU minimization and material consolidation. Finally, the protection of sensitive fissile materials, such as HEU, is an area that provides opportunities for international cooperation in the form of the exchange of best practices, the development of common standards, and threat assessments that could help strengthen the global nuclear security regime.

This chapter considers the legal and organizational aspects of the nuclear security arrangements that exist in Russia, with special emphasis on the considerations that are relevant for the minimization of HEU use in research reactors and other civilian facilities. Although the focus of the chapter is on Russia, most of the approaches to nuclear security implemented there are based on universally accepted principles, so similar considerations are likely to be applicable elsewhere. Russia's nuclear security experience could prove valuable in identifying opportunities for a better coordination of the effort to strengthen the nuclear security arrangements worldwide; it could also foster a better understanding of the challenges that are involved in managing HEU minimization in Russia and elsewhere.

In this chapter, nuclear security is defined as a combination of physical protection and material control and accounting measures. According to the definition accepted in Russia's regulations, "physical protection is a system of measures aimed at prevention of nuclear material theft or sabotage against nuclear material or nuclear facility, as well as mitigation and response in case of theft or sabotage." Material control and accounting is defined as "a system of measures aimed at definition of nuclear materials quantity, ensuring continuity of information about nuclear material, control over operations with nuclear material, prevention and timely detection of nuclear material losses and thefts."

This chapter will consider, in turn, the structure of Russian nuclear security regulations, the roles and responsibilities of the government agencies involved, nuclear facility operators and protective forces, the graded approach to protecting nuclear materials in Russia, and the impact of higher nuclear security requirements on the operation of facilities.

Although most Russian research reactors are civilian facilities, a significant number of research installations have been used in defense-related research or have been managed by the research institutes that are part of the nuclear weapon complex. Many organizations carry out both civilian and defense-related work. Nuclear security arrangements at defense facilities are different from those in the civilian sector, particularly when it comes to the structure of regulatory oversight. However, as far as HEU reactors and other similar facilities are concerned, the differences are not particularly large. Those differences are discussed in this chapter where appropriate.

Nuclear security regulations in Russia

Regulations are key to a robust nuclear security system. They establish the goals for nuclear security activities, define the responsibilities of the entities and individuals involved and provide guidance regarding implementation of the responsibilities. Regulations also capture existing best practices, ensure uniformity in the implementation of those practices and provide criteria to evaluate performance and compliance.

The system of regulations that exists in Russia today includes several tiers of documents that govern various aspects of nuclear security:

- Federal laws establish basic requirements for activities in any area, including nuclear industry and its respective security arrangements;
- Government decrees define the responsibilities of all stakeholders and interactions between them, as well as key nuclear security requirements;
- Federal Norms and Rules (FNP) establish requirements for organizations involved in specific activities.[279] The FNP relevant to nuclear security define detailed mandatory requirements in the implementation of certain safety or security related measures at nuclear sites or with nuclear materials. FNP-type documents apply only to civilian applications of nuclear energy;
- Agency-level regulations define requirements specific to nuclear facilities subordinated to individual agencies involved in nuclear activities; and

- Various methodological documents, guidelines, and standards, typically issued by individual agencies, provide non-binding guidance intended to help nuclear sites to ensure compliance with higher-level mandatory requirements.

International obligations

There are no international legal agreements that impose specific nuclear security related requirements on the domestic nuclear activity of its members. One notable exception is the safeguards administered by the International Atomic Energy Agency (IAEA) in non-nuclear weapon states that are members of Nuclear Nonproliferation Treaty (NPT). The safeguards are limited, however, to nuclear materials accounting and control and do not impose any obligations regarding physical protection of the material. Moreover, since Russia is a nuclear weapon state member of the NPT, it is not required to implement the material accounting and control measures that are part of the IAEA safeguards arrangements.

The other important exception is the Convention on the Physical Protection of Nuclear Materials (CPPNM) that requires its members to provide a certain level of physical protection to nuclear materials in international transport. An amendment to the CPPNM adopted in 2005 covers some categories of domestic civilian nuclear material as well. There are other international agreements that deal with various aspects of nuclear security, such as the United Nations Security Council Resolution 1540 and the International Convention on Suppressing Acts of Nuclear Terrorism, but none of them imposes legally binding obligations on national nuclear security systems or provide specific guidance.[280]

In the absence of legally-binding obligations, various aspects of domestic nuclear security are covered by voluntary application of the recommendations on physical protection issued by the IAEA.[281] Russian regulations normally explicitly state that they take the international recommendations into account, so they incorporate most of the principles included in the IAEA recommendations.

Federal laws and governmental decrees

The federal law “On Atomic Energy Use,” adopted in 1995, is the main Russian law regulating civilian nuclear energy applications. Among other things, it establishes fundamental requirements with regard to nuclear materials physical protection and accounting and control. The law does not apply to the design, manufacturing, testing, operation and disposal of nuclear weapons and military use nuclear energy facilities such as naval propulsion.[282]

Specifically, the law prohibits operation of nuclear sites, as well as any other activity with nuclear materials in any form and at any stage of production, use, reprocessing, transportation and storage, without implementing physical protection measures approved by regulators. The law also requires that any nuclear material, regardless of ownership rights, must be subject to accounting and control in the state accounting and control system. The law assigns to organizations operating nuclear facilities responsibility for nuclear materials physical protection, accounting and control.

There is no similar federal law that would govern nuclear materials and facilities in military use, such as nuclear weapons and nuclear propulsion reactors. Attempts to develop such a law have been made since the late 1990s, but they have been unsuccessful so far.

While federal laws in Russia create a general legal framework, specific obligations and requirements are normally contained in governmental decrees. There are two government decrees specifically devoted to nuclear material physical protection and accounting and control. The first one, establishing the Rules of Physical Protection of Nuclear Materials, Nuclear Sites and Nuclear Material Storage Points (Physical Protection Rules), was enacted on July 19, 2007.[283] The second decree, which established the Regulation on the System of State Accounting and Control of Nuclear Materials (MC&A Regulation), was enacted on May 6, 2008.[284] Article 1 of the Physical Protection Rules notes that they were developed "with due consideration of the international commitments of the Russian Federation and IAEA recommendations for the physical protection of nuclear material and nuclear facilities."

The Physical Protection Rules apply to both civilian and military nuclear materials. They introduce a "state system of physical protection," define participants of the system, and state their roles and responsibilities. The rules also define key requirements that are imposed on nuclear sites and nuclear materials in transportation. One of the important definitions set by the rules is that of categories of nuclear materials, which is later used to define a graded approach to protection of specific sites and materials.

Unlike the Physical Protection Rules, the MC&A Regulation applies only to civilian nuclear materials, while leaving outside of its scope the nuclear materials used in the development, manufacturing, testing, operation and disposal of nuclear weapons and other military applications. MC&A Regulation contains a list of nuclear materials subject to accounting and control, but does not introduce categorization of these materials, delegating this to lower level regulations. The MC&A Regulation defines stakeholders involved in the System of State Accounting and Control of Nuclear Materials (SSAC) and their roles and responsibilities. It also defines key requirements imposed on material accounting and control systems at specific facilities, as well as at the federal level.

Federal norms and rules

Detailed mandatory requirements that guide implementation of physical protection and material accounting and control at individual facilities that handle nuclear materials are established in the Federal Norms and Rules (FNP). These documents are issued and approved by the federal regulator, the Federal Service for Ecological, Technical and Nuclear Oversight (Rostekhnadzor), although this process could be initiated by any agency that is involved in the regulated activity. Technically, the Rostekhnadzor regulations apply only to civilian facilities and activities, but, as discussed later, in a number of cases, they are used outside of the civilian domain.

The two most important FNPs are the Requirements to the Systems of Physical Protection of Nuclear Materials, Nuclear Sites and Nuclear Material Storage Points (Physical

Protection Requirements) and the Basic Rules of Accounting and Control of Nuclear Materials (known as OPUK for its Russian acronym).[285] There are several other FNPs applicable to physical protection and material accounting and control: on physical protection of nuclear materials during transportation, physical protection of nuclear powered ships and ships transporting nuclear materials, requirements for material balance areas, and rules for reclassifying nuclear materials to radioactive substances or radioactive waste. All these regulatory documents take the relevant IAEA recommendations into account and generally follow the IAEA guidance.

The Physical Protection Requirements cover the following issues related to physical protection at nuclear sites:

- Categorization of items subject to physical protection, as well as rooms, buildings, and territories to be protected;
- Procedures for development, upgrade, and operation of physical protection systems;
- Requirements for a physical protection system and its components, including organization measures, personnel and equipment;
- Requirements for the physical protection system zoning.

In addition to nuclear materials, items subject to physical protection include critical elements of a nuclear site that, if sabotaged, could lead to catastrophic consequences, including the massive release of radioactivity. An example of such a critical element is the cooling system of a nuclear power reactor. Categorization takes into account the category of nuclear material subject to protection (based on its isotopic content and physical form), secrecy (classification level) of a material or a component of the facility, and potential consequences of unauthorized action against protected materials or components. Zoning is introduced to facilitate a graded approach to protection, depending on the category of protected material or element inside the physical protection system (see Table 6.3).

The OPUK material accounting and control regulations contain the following provisions:

- Guiding principles of nuclear material accounting and control;
- Nuclear and other special materials subject to accounting, including types of material and threshold quantities, and categories of nuclear materials for the MC&A purposes;
- Material balance areas and key measurement points;
- Principles of nuclear material measurements;
- Rules for transfers of nuclear material;
- Rules governing conduct of physical inventories, including frequency requirements depending on the category of nuclear material;
- Criteria for an MC&A anomaly;
- Description of accounting and reporting documentation;
- Requirements to a nuclear materials control and accounting system at individual facilities;

Agency regulations

Multiple agency-level regulations have been developed to elaborate on requirements established in higher-level regulations. These regulations normally deal with activities that are specific to the agency. At this level, regulations do not necessarily distinguish between civilian and defense use of the material, concentrating instead on requirements applied to individual facilities that may involve a range of activities. The agencies that handle significant amounts of nuclear material, such as Rosatom or the Ministry of Industry and Trade, have developed sets of regulations covering all MC&A aspects in detail. The Ministry of Industry and Trade regulates activities at its shipbuilding plants. Other agencies, for example the Russian Academy of Sciences, normally have a much poorer regulatory base, so they have to rely on nuclear security guidelines issued by Rostekhnadzor.

Agency-level regulations normally apply to all sites and activities under specific agency authority, both civilian and defense-related. From a regulatory point of view, the nature of an activity is linked to the type of license that an operator is required to obtain. Many operators hold multiple licenses and can conduct both kind of activities, often with no physical separation between equipment and workshops involved in civilian and defense work. It is, therefore, reasonable to assume that there are few, if any, differences between regulations that govern nuclear security arrangements in civilian and defense facilities.

Responsibility for nuclear materials security

There are several types of stakeholders with responsibility for nuclear security:

- Federal agencies that manage nuclear sites,
- Regulatory bodies,
- Federal agencies that support nuclear security,
- Operators of nuclear facilities, and
- Contractors that provide various nuclear security related services to operators and federal agencies.

There are several federal agencies that have nuclear facilities under their control and are, therefore, responsible for physical protection and MC&A.

- The Rosatom State Nuclear Energy Corporation manages most of the Russian nuclear complex, including most of the fissile material stockpile;[286]
- The Ministry of Defense controls nuclear weapons and nuclear powered submarines and surface ships (and their fuel). The ministry also has some research facilities that conduct defense-related work;
- The Ministry of Industry and Trade controls shipyards that build nuclear submarines and nuclear powered surface ships and provides technical maintenance and repair services. Shipyards load and unload naval reactor cores and handle significant volumes of fresh and irradiated nuclear fuel;

- The Federal Agency for Marine and River Transportation is in charge of ports that handle nuclear materials during transportation, as well as non-nuclear ships involved in nuclear materials transportation. In the past, this agency also operated nuclear-powered icebreakers and nuclear service ships; these activities were transferred to Rosatom in 2008;
- The Ministry of Education and Science manages universities that operate research reactors; and
- The National Research Center "Kurchatov Institute" has special status as a federal state entity and operates a number of nuclear reactors and other research facilities.

These agencies manage nuclear security at subordinate organizations by issuing agency-level regulations, coordinating facility activities and implementing internal monitoring. Certain facility management decisions related to nuclear security also require reconciliation and approval from superior agencies. In addition, Rosatom performs interagency coordination and overall system management functions and provides support to decision making at the policy level. Rosatom also maintains a federal registry of nuclear materials and manages nuclear materials on federal property.

Regulatory oversight

Three agencies have nuclear security regulatory functions in physical security and material control and accounting:

- The Federal Service for Environmental, Technical and Nuclear Oversight (Rostekhnadzor) regulates nuclear materials in civilian use. It approves Federal Norms and Rules, conducts licensing of nuclear facilities and organizations providing various services to nuclear facilities, and implements oversight through data gathering, inspections and sanctions;
- Rosatom is in charge of licensing of defense-related nuclear activities. Rosatom issues licenses to both Rosatom and non-Rosatom organizations. This function is implemented by Rosatom's Department of Nuclear and Radiation Safety, Licensing and Approval Activity; and
- The Ministry of Defense implements oversight over nuclear materials in military use. Once a facility obtains a license for military nuclear activity from Rosatom, it is subject to inspection by MOD's Department of State Oversight over Nuclear and Radiation Safety/Security. Rosatom provides subject matter expertise to support the Ministry of Defense in implementing its regulatory functions.

Multiple agencies support nuclear security related activities. Notably, the Ministry of Interior (MVD) provides protective forces, the Federal Security Service (FSB) provides intelligence support, personnel background checks and takes part in emergency response, and the Federal Agency for Standardization and Technical Regulation provides metrology and standardization support.

Nuclear facility operators are in charge of nuclear security at specific nuclear sites. An operator is a legal entity that operates a nuclear site, including buildings, facilities and equipment, and handles nuclear materials as part of its production process. An operator can be a state owned or private organization. However, private organizations must receive governmental approval to be eligible to own and operate nuclear facilities.

Regardless of ownership, a nuclear facility operator must obtain a license to operate nuclear facilities and handle nuclear materials. Licenses for civilian activities are issued by Rostekhnadzor, while licenses for defense activities are issued by Rosatom. In accordance with Russian legislation, nuclear facility management bears the ultimate responsibility for nuclear security at a site. One of the mandatory qualifications to obtain a license is the ability to ensure proper physical protection, accounting and control of nuclear materials. An operator's capability to ensure nuclear security is validated during the licensing process through a review of documentation and on-site inspections.

To perform their nuclear security related functions, nuclear sites can utilize contractors to provide various services, such as systems design, equipment supply, installation and setup, vulnerability analysis and system effectiveness evaluation, and personnel training. Organizations providing certain nuclear security-related services must obtain a Rostekhnadzor license to perform their work.

Physical protection

According to Physical Protection Rules, nuclear sites must be provided with armed guards—protective forces, usually referred to as pro-forces. Protective forces operate physical protection equipment installed along a nuclear site's perimeter and implement access control. There are three different types of protective forces:

Internal Troops of the Ministry of the Interior (MVD VV) are federally funded paramilitary troops with the right to use automatic weapons. The MVD VV units consist of a mix of professional soldiers and officers, as well as conscripts, which is commonly considered a weakness.

Agency protective forces are dedicated security organizations that report to the specific agency that manages nuclear facilities. Agency forces consist of professional officers, but they have restrictions on the use of weaponry, such as automatic guns, and other special means that are available to MVD VV. Rosatom's protective force organization is called Atomokhrana. Agency protective forces often work jointly with MVD VV, with the latter being in charge of perimeter and outer areas of a nuclear site and the agency forces guarding the inner, most critical areas.

MVD Commercial Guards are commercial providers of security services managed by the General Administration for Private Security of the Ministry of the Interior. They are typically involved in the protection of minor nuclear sites and non-nuclear sites handling nuclear materials, such as ports.

The protection arrangements at individual sites vary depending on the required level of protection. Some facilities are eligible for protection by MVD VV, which is assigned by a government decree. The decree is not released to the public, but the list is believed to include most nuclear sites that handle category 1 and 2 nuclear materials (see the categorization below). It is likely to include all facilities of this class.

Security at the sites that are not eligible for the MVD VV protection can be provided by the agency protective forces. A facility can rely on the agency forces or contract out protection services to Atomokhrana, which has the right to work at non-Rosatom sites, or to the MVD commercial guards, provided they are licensed to provide the required level of protection. Normally, this is done as a contract between a facility and the protective force organization that provides the services.

Funding of nuclear materials security

The cost of maintaining nuclear security can be one of the key factors in making decisions regarding the minimization of the use of HEU. Normally, nuclear security measures can be funded from three different sources: a facility's own funds, its agency budget (Rosatom in particular with regard to nuclear facilities), and the federal budget. Foreign assistance has also has been a significant source of financial support for nuclear security in Russia over the last two decades.

Ideally, a nuclear site should be able to fund nuclear security activities from its own budget. The law "On Atomic Energy Use" required nuclear sites to maintain financial resources sufficient to perform their functions and particularly to support its material protection, control and accounting system. The ability of an organization to fund nuclear security measures at its sites is one of the conditions for obtaining a license to operate. In practice, however, the level of detail of disclosure of financial information during the licensing process and the rigor with which Rostekhnadzor validates this information is often insufficient for a reliable conclusion regarding the financial viability of the license applicant.

Nuclear security regulatory documents explicitly list the kind of activities that each nuclear site has to provide funding for. If a site is eligible for protection by the Ministry of the Interior troops (MVD VV), however, the cost of that protection is borne by the ministry, which is funded by the federal budget. The sites that are not eligible for this protection must pay for agency protective forces or outside contractors, so, under such circumstances, each facility bears the full cost of the protection service. As noted earlier, agency forces may be hired to perform certain functions even at those sites that are protected by the Ministry of the Interior, so it is likely that all operators pay at least some of the cost of nuclear security services.

In the past, Rosatom paid for pro-forces services at its own facilities from the agency budget, but this model has been discontinued. Today, nuclear facilities can still use agency funding, although in an indirect way, by requesting financial support. To obtain this support, the operator must prepare a funding support request with justification and submit it to its managing agency. In the case of Rosatom, the agency can use several sources to provide funding support to its nuclear sites. These sources are its special reserve, income from Rosatom activities and federal budget funding. Information about funding arrangements at other agencies is not available, but it is likely to be similar to those of Rosatom.

According to the law that created Rosatom as a state corporation, Rosatom maintains a special reserve fund for nuclear security expenditures based on contributions from subordinated nuclear sites and other organizations that operate nuclear facilities or handle radioactive materials. Contributions to Rosatom's special reserve fund for nuclear security (as well as other Rosatom reserve funds) are mandated by a governmental decree that gives Rosatom the authority to determine the size of the contributions, but establishes a ceiling of 2% of the revenue that an organization receives from nuclear-related activity.

Rosatom also takes part in developing the federal budget that may include nuclear security expenditures. Federal budget support for nuclear security is provided through either federal target programs or through direct subsidies. Some funding for nuclear security is being provided by the Federal Target Program on Nuclear and Radiation Safety for 2008–2015. The federal budget also provides nuclear security-related funding through the federal agencies that handle certain aspects of nuclear security, such as the Ministry of the Interior or the Federal Security Service (FSB).

Categorization of nuclear materials in Russia

Categorization of nuclear materials plays a very important role in determining the structure of physical protection and material control and accounting measures that have to be implemented at nuclear facilities. In Russia, categories of materials defined for physical protection regulations are different from those used for the purposes of material control and accounting.

Material categories defined in the physical protection rules are similar to those established by the IAEA guidance documents. The only difference is the categorization of irradiated nuclear fuel, which in Russia is considered a Category 2 material, as opposed to Category 3 in the IAEA guidelines. This categorization is provided i n Table 6.1. The categorization of nuclear materials for the purposes of material control and accounting, established by the OPUK regulation, is provided in Table 6.2.

Type of material	Isotopic contents	Category of nuclear material, based on its mass M in kilograms			
		1	2	3	4
Pu, fresh or slightly irradiated	Less than 80% Pu-238	$M \geq 2$	$0.5 < M < 2$	$0.015 < M < 0.5$	—
U-235, fresh or slightly irradiated	More than 20% U-235	M≥5	$1 < M < 5$	$0.015 < M \leq 1$	—
	Less than 20% and more than 10% U-235	—	M≥10	$1 < M < 10$	—
	Less than 10% and more than natural content of U-235	—	—	M≥10	—
U-233, fresh or slightly irradiated	Any enrichment	$M \geq 2$	$0.5 < M < 2$	$0.015 < M < 0.5$	—
Any irradiated nuclear material, including natural or depleted uranium and thorium	Content of fissile isotopes before irradiation is less than 10%	—	Any mass	—	—
	Content of fissile isotopes before irradiation is more than 10%	—	Mass corresponding to category 1 of fresh or lightly irradiated nuclear material	Mass corresponding to categories 1 and 2 of fresh or lightly irradiated nuclear material	—
Np-237, Am-241, Am-243, Ca-252	Any	—	—	—	Any mass

Table 6.1. Categories of nuclear material for the purposes of physical protection.

Form of nuclear material	Nuclear material	Category of nuclear material, based on its mass M in kilograms			
		1	2	3	4
Metal product: Metal product and billets; ingots, small pellets/meal, and their alloys and mixtures; fuel elements and assemblies containing metallic and intermetallic fuel; defective product and waste reprocessed by smelting	Pu, U-233	M ≥ 2 for the total mass of Pu and U-233	0.5 ≤ M < 2 for the total mass of Pu and U-233	0.2 ≤ M < 0.5 for the total mass of Pu and U-233	M < 0.2 for the total mass of Pu and U-233
	HEU [U-235 content is no less than 20%]	M ≥ 5 for U-235 isotope	1 ≤ M < 5 for the U-235 isotope	0.5 ≤ M < 1 for the U-235 isotope	M < 0.5 for the U-235 isotope
	Mixture, aggregate of Pu, U-233, HEU, and other nuclear materials	M ≥ 2 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf	0.5 ≤ M < 2 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf	0.2 ≤ M < 0.5 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf	M < 0.2 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf
Product with high nuclear material content: Carbides, oxides, chlorides, nitrides, fluorides, and their alloys and mixtures; Fuel elements and assemblies containing fuel from the compounds mentioned above; other product with a concentration (content) of nuclear material not less than 25 g/l (25 g/kg)	Pu, U-233	M ≥ 6 for the total mass of Pu and U-233	2 ≤ M < 6 for the total mass of Pu and U-233	0.5 ≤ M < 2 for the total mass of Pu and U-233	M < 0.5 for the total mass of Pu and U-233
	HEU	M ≥ 20 for U-235 isotope	6 ≤ M < 20 for the U-235 isotope	2 ≤ M < 6 for the U-235 isotope	M < 2 for the U-235 isotope
	Mixture, aggregate of Pu, U-233, HEU, and other nuclear materials	M ≥ 6 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf	2 ≤ M < 6 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf	0.5 ≤ M < 2 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf	M < 0.5 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf
Product with low nuclear material content: Product requiring complex processing; product with a concentration (content) of nuclear material from 1 to 25 g/l (from 1 to 25 g/kg)	Pu, U-233		M ≥ 16 for the total mass of Pu and U-233	3 ≤ M < 16 for the total mass of Pu and U-233	M < 3 for the total mass of Pu and U-233
	HEU		M ≥ 50 for the U-235 isotope	8 ≤ M < 50 for the U-235 isotope	M < 8 for the U-235 isotope
	Mixture, aggregate of Pu, U-233, HEU, and other nuclear materials		M ≥ 16 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf	3 ≤ M < 16 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf	M < 3 for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf
All other product, including: product containing Pu, U-233, and HEU with a concentration (content) less than 1 g/l (1 g/kg); any uranium compounds with a U-235 content less than 20%; any product generating an absorbed dose rate at 1 m without shielding less than 1 Gy/hr = 100 rad/hr; any compounds: with plutonium (with a Pu-238 content less than 60%), thorium, neptunium-237, americium-241, americium-243, and californium-252; special non-nuclear materials and any compounds with them					The total mass of all nuclear materials not less than the minimum quantities of material subject to accounting

Table 6.2. Categories of nuclear material for the purposes of material control and accounting. (Unless otherwise noted, Pu denotes plutonium of any composition that contains no more than 60% Pu-238.)

The differences in categorization may lead to confusion in applying certain requirements, such as the use of the two-person rule, when working with higher categories of nuclear materials. This confusion is resolved at the site level, through the development of site procedures that comply with both physical protection and MC&A requirements.

Requirements for nuclear materials security depending on their category

The physical protection and material control and accounting regulations establish a set of measures that have to be applied to nuclear material in each category. According to the physical protection rules "when establishing (or upgrading) a physical protection system, the nuclear site must … establish requirements for administrative and technical physical protection measures based on the category of the objects of physical protection." For material control and accounting, OPUK requires that "nuclear material within MBAs [material balance areas] shall be categorized in order to provide a differentiated approach to determining nuclear material control and accounting procedures and methods."

Categorization of the objects of physical protection is one of the key steps of the physical protection system design process. The category of the object of physical protection depends on three factors: the category of nuclear material, consequences of unauthorized action against the object, and secrecy of information. Obviously, the category of nuclear material is the most important characteristic of nuclear material that is being protected. For other objects of physical protection, such as critical elements of the nuclear facility or physical protection system design documentation, the nuclear material category may have no role at all. In this case, the most important factors are the consequences of unauthorized action or violation of information secrecy. The resulting categorization of protected items is summarized in Table 6.3.

A nuclear site needs to establish a zoning system to provide different protection levels for different categories of protected materials and items. Russian regulations distinguish three types of areas or zones: a protected area, an internal area and a vital area, with the protected area being least protected and the vital area being the most protected. For a generic HEU reactor site the perimeter of the site would be the protected area, the reactor or storage building would be the internal area, and the reactor itself or a specific nuclear material storage vault within the building would be the vital area. Certain sites that do not handle highly attractive nuclear material may have protected and internal areas only, without a vital area being established. Regulations establish graded requirements for protection of each type of zone. The higher is the category of zone, the tougher are the requirements to detection and delay capabilities of technical and organizational measures used to protect this zone. These measures, and the specific equipment that is used in each protected area, are described in agency-level regulations. These documents are not publicly available, but they appear to adopt an approach that establishes basic requirements for the protected area, with enhancements added for the inner and vital areas.

While the detailed protection arrangements are classified, the physical protection rules establish general requirements that specify the relationship between protected areas and categories of items that they may contain. These requirements are summarized in Table 6.3. As can be seen from the table, the categorization uses the physical protection category of the material (Table 6.1), the classification level of the protected item, and the consequences of unauthorized actions. The consequences are divided into three categories:

- Category I: Unauthorized actions could result in a nuclear or radiological impact that affects one or more subjects of the Russian Federation [such as *oblast'*] or affect areas outside of the Russian Federation.
- Category II: Nuclear or radiological consequences of unauthorized actions could affect areas beyond the sanitary protection zone[287].
- Category III: Nuclear or radiological consequences of unauthorized actions could affect areas beyond the buildings, but contained within the sanitary protection zone.

These categories appear to be based on the scenario of an accident that results in a radioactive contamination of areas outside of the facility. Although it is not mentioned explicitly, the "nuclear or radiological" consequences take into account the threat of nuclear terrorism and threats related to nuclear-proliferation.

In addition to the classification based on the categories of materials and items defined in the national regulations, the categorization uses the term "significant quantity of direct use nuclear material," which is placed in Category A, afforded the highest level of protection. The definition of this term follows the one given in the context of IAEA safeguards regarding the isotopic composition of the material.[288] However, the rules do not explicitly specify what quantities of nuclear material would be considered significant.[289]

The rules also leave some room for flexibility in choosing additional security measures that would be implemented in the vital and internal areas. In practice, the need for additional measures is determined by system designers, based on system effectiveness requirements established by the site management. In addition to enhanced equipment requirements, nuclear material stored in the vital area also requires use of the two-person rule, when accessing it. Application of the two-person rule to internal areas or specific activities at a site, such as the inspection of vehicle leaving the site, is at the discretion of the site management. This decision is made based on evaluation of overall effectiveness of the physical protection system.

In most cases, HEU at nuclear reactor sites, which is a category 1 or 2 material from the physical protection point of view, would be placed at least in the internal area. From the general guidelines that are available publicly, it is difficult to say with certainty if particular HEU minimization measures, such as conversion of a reactor to LEU fuel or removal of HEU from a site, would result in significant changes to the security arrangements. Since most of these arrangements are site-specific, an operator could probably initiate a review that would result in reclassification of the protected areas.

In addition to enhanced protection at a site, category 1 and 2 nuclear materials require special protection measures during transportation. Requirements for the transportation of these materials include the use of specially equipped vehicles (truck, railcar, ship or plane), sealed containers, and armed guards and escorts.

Category	Characteristics of the object of physical protection	Area where the object of physical protection is sited
A	At least two of the following are true: Category 1 nuclear material Security classification "Special importance" Category I consequence of unauthorized actions	Vital area provided with additional physical protection and security equipment (if necessary)
A	Significant quantity of direct use nuclear material	Same as above
B	At least one of the following is true: Category 1 or Category 2 (when accumulation of material to Category 1 is possible) nuclear material Security classification "Special importance" Category I consequence of unauthorized actions	Vital or internal area provided with additional physical protection and security equipment (if necessary)
B	At least two of the following are true: Category 2 nuclear material Security classification "Top secret" Category II consequence of unauthorized actions	Vital or internal area provided with additional physical protection and security equipment (if necessary)
C	At least one of the following is true: Category 2 nuclear material Security classification "Top secret" Category II consequence of unauthorized actions	Internal area
D	At least one of the following is true: Category 3 nuclear material Security classification "Secret" Category III consequence of unauthorized actions	Protected area or protected area outfitted with additional physical protection and security equipment (if necessary)
E	Other objects of physical protection	Restricted access area

Table 6.3. Requirements for siting protected items at Russian nuclear facilities.

From the point of view of material control and accounting, HEU that is used in research facilities largely falls into category 1 or 2 of the MC&A categorization scheme. However, some facilities use small amounts of HEU, which might be classified as category 3 or 4 material.

For category 1 and 2 nuclear materials, rooms, containers and other equipment that holds them must be sealed with uniquely identifiable tamper indicating devices. All materials are subject to periodic inventory in the designated material balance areas. For materials in categories 1 and 2, the interval between inventories is two and three months, respectively. The intervals for the category 3 and 4 materials are six and twelve months. The inventory procedures may involve a check of documentation and of attributes of the material as well as measurements of its physical characteristics.[290] The inventory may use a sampling approach, with the size of the sample being larger for higher categories of material.

Impact of higher nuclear security requirements on operations of facilities

The higher security requirements associated with the use of HEU have an impact on operations at sites where HEU is present. An outline of the impact each security requirement discussed above has on site operations is provided below.

Establishing internal or vital areas for handling or storing HEU will lead to a more complex site layout, with additional requirements for space needed to ensure proper zoning and building locations on a site. This will also require additional access control measures, such as additional procedures and a larger amount and enhanced quality of entry control points with proper access control equipment and personnel. Enhanced access controls require more rigorous management oversight and additional human resources to maintain the controls. Additional time is needed to conduct initial personnel screening and keep it updated. Also, operations at the site are affected by the time required to get from the outside to the workplace, located behind multiple layers of access control, on a daily basis.

Higher physical protection equipment requirements in internal and vital areas increases the capital costs associated with the design, procurement, installation, and testing of the equipment, and training of personnel. Operation costs are increased as well, as additional personnel are required to operate, maintain, and repair the equipment.

Transportation security requirements also increase the cost of labor and equipment, as they call for specialized vehicles and containers, armed escorts, and communication setup during transportation. Transportation also requires additional advance planning and may involve coordination with other agencies and organizations.

Frequent physical inventories creates significant disruption for site operation, as all nuclear material movements must be stopped, unless continuous operation is justified by the site's technology process (typical for industrial-scale nuclear fuel cycle facilities). Thus, an increased frequency of physical inventories leads to a propotional increase in nuclear facility shutdown time. It also leads to higher radiation doses received by the personnel involved in the inventory. To get a better understanding of the scale of resources required to conduct a physical inventory, one may note the fact that the resources required is one of the key reasons why an initial physical inventory still has not been completed for most of the nuclear sites in Russia, including research sites with small quantities of HEU. Paper-based legacy records are used in the current inventory procedures, even though this practice may not be fully compliant with the current regulatory requirements.

Unique tamper indicating devices that are required for handling nuclear materials of higher categories could also increase the capital and operational costs somewhat. In addition to the cost of the seals, there is a cost associated with developing and maintaining the infrastructure required to apply, handle and account for seals.

Implementation of the **two-person rule** essentially requires twice as many personnel, with the appropriate qualifications and clearance, to perform the same operation.

In addition to the specific requirements outlined above, higher security requirements at a specific site mean higher intensity oversight from the regulatory agencies, such as Rostekhnadzor or the Ministry of Defense, as well as from federal agencies managing the site. Inspections associated with this oversight also cause disruptions in site operation and distract personnel from their core responsibilities. Also, if incompliance is detected during an inspection, it may lead to sanctions in terms of fines, license suspension or withdrawal, and disqualification of senior management in charge of security.

Overall, higher security requirements for sites working with HEU impose a certain burden on the site operator in the form of higher material and labor costs associated with implementation of the enhanced requirements. Higher security requirements also lead to disruptions in site operations, due to procedures not associated with core site operations, such as taking inventory or oversight inspections. However, the additional cost does not appear to be prohibitively high, so operators rarely have economic incentives to remove HEU from their sites.

7 Russian/Soviet naval reactor programs

Introduction

The first Soviet nuclear-powered submarine, the K-3 *Leninskiy Komsomol*, of the Project 627/November class, was launched on August 9, 1957. The submarine's nuclear reactors were started just over a month later, on September 14, 1957. By 2015, Soviet and Russian shipyards had built more than 250 nuclear submarines, as well as five military and 10 civilian nuclear-powered ships (see Figure 7.1). In addition, the total number of naval reactors built in Russia had reached almost 500, most of them light-water reactors. However, as of 2017, less than 100 of those reactors remain in operation on 54 nuclear submarines and nine military and civilian ships. More than half of these ships and submarines are currently undergoing or awaiting repairs and some of the vessels now awaiting repairs will probably be decommissioned and dismantled instead.

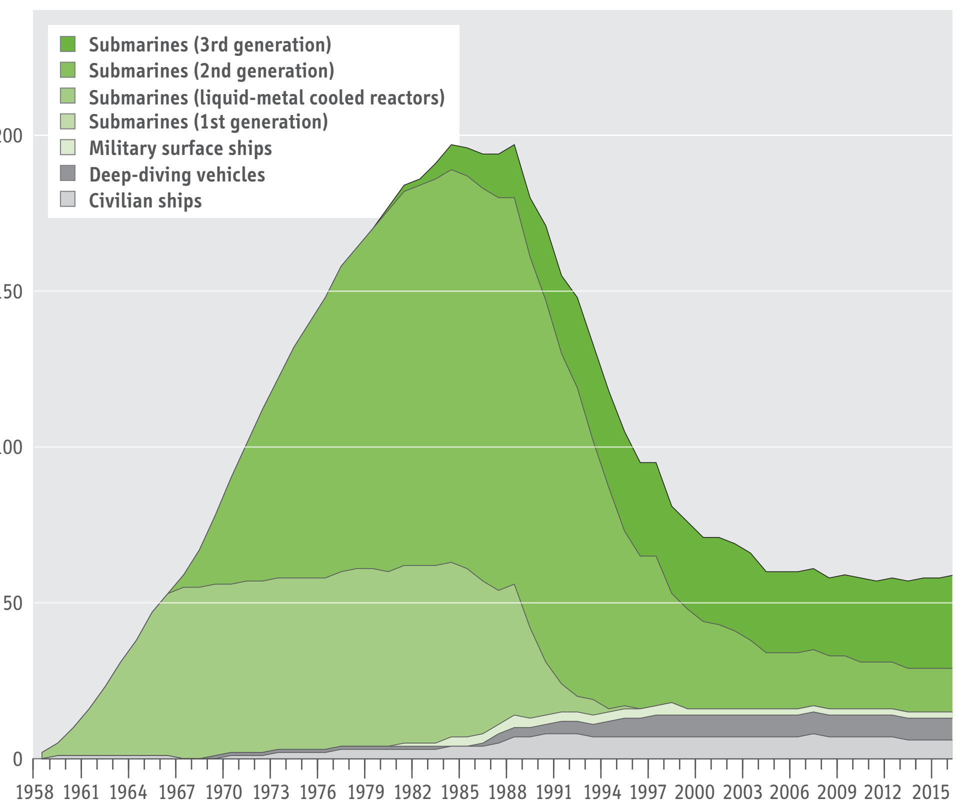

Figure 7.1. Number of Soviet/Russian nuclear-powered ships in service by type and generation.

Still, Russia continues to build nuclear submarines and icebreakers. Under the 2020 State Armament Program, Russian shipyards are to build eight Project 955/955A (Borey class) strategic and seven Project 885/885M (Yasen class) multipurpose nuclear submarines. New icebreakers are also being built for the civilian fleet; the first of these, which will be fueled by LEU, is expected to enter into service after 2017. Since Russia is decommissioning old nuclear-powered vessels faster than it builds new ones, the overall number of operational naval reactors will continue to decline over the next several years.

This chapter presents an overview of the history of Russian naval reactor technology. It also analyzes the current state of the Russian nuclear fleet and the scale of the program to decommission nuclear-powered ships and submarines.

Manufacturing base for the Russian nuclear fleet

Historically, nuclear-powered submarine design expertise was concentrated at three Russian design bureaus: the Rubin Central Design Bureau (Leningrad/St. Petersburg), the Malakhit Naval Machine-Building Bureau (St. Petersburg), and the Lazurit Central Design Bureau (Gorky/Nizhniy Novgorod). Nuclear-powered surface ships and icebreakers were designed by the Severnoye Design Bureau, the Iceberg Central Design Bureau, and the Baltsudproyekt Central Design Bureau, all based in St. Petersburg. Nuclear submarines were built at the Sevmash shipyard in Severodvinsk, the Amursk Shipbuilding Plant in Komsomolsk-on-Amur, the Krasnoye Sormovo shipyard in Nizhniy Novgorod, and the Admiralty Plant (renamed the Admiralty Association in 1972) in St. Petersburg. Nuclear-powered surface ships and icebreakers were built at the Baltiyskiy Plant in St. Petersburg, the Zaliv plant in Kerch, and the Wärtsilä shipyard in Finland (see Figure 7.2).

Figure 7.2. Locations involved in the development and construction of Soviet and Russian nuclear-powered ships and naval nuclear reactors.

The vast majority of naval reactor units built in Russia (95% of the reactors and 75% of their steam generators) were designed by the Experimental Design Bureau of Machine-Building (OKBM) in Nizhniy Novgorod.[291] Some reactors were designed by the Scientific Research and Design Institute of Power Engineering (NIKIET) in Moscow, by the Institute of Physics and Power Engineering (IPPE or FEI) in Obninsk, and by the Gidropress Experimental Design Bureau (OKB Gidropress) in Podolsk. The latter designed liquid metal-cooled (LMC) reactors. The reactor manufacturing centers included several in Nizhniy Novgorod, Podolsk (that produced reactor units of the BM-40/A type), Leningrad (V-5) and Sosnovy Bor (VAU-6).[292]

Russia's nuclear submarines and warships serve with Russia's Northern and Pacific Fleets on several bases on the Kola Peninsula and in Kamchatka. The nuclear icebreakers, currently operated by the company Rosatomflot, are all based in Murmansk.

Nuclear submarines undergo repairs and maintenance, including refueling, at facilities operated by the United Shipbuilding Corporation (OSK). These facilities include Sevmash and Zvezdochka plants in Severodvinsk, Nerpa in Snezhnogorsk, the Zvezda Far Eastern Plant in Bolshoy Kamen, the Northeastern Repair Center (SVRTs) in Vilyuchinsk, and others. They also dismantle Russian nuclear submarines after they are decommissioned. As part of that process, after unloading the spent nuclear fuel, they remove the reactor compartments, seal them, and put them into long-term in land-based storage facilities specially built at Sayda Bay, Murmansk Region, and Cape Ustrichnyy (Razboynik Bay), Primorsky Krai. Figure 7.3 shows locations of facilities that are involved in the production of naval fuel and the management of spent fuel from naval reactors.

Figure 7.3. Fuel-related facilities (production, refueling, storage, and reprocessing).

Naval reactors

Nuclear-powered submarine reactors

Light-water reactors

The first-generation nuclear reactor installed on submarines, VM-A, was a light-water reactor with a nominal thermal power 70 MW. Two reactors were installed in each submarine.[293]

Fifty-five nuclear submarines of five different types, produced during 1958–1968, were equipped with these reactors. The submarines remained in service until the early 1990s. Almost all were de-fueled and dismantled during 2000–2010.

Second-generation naval propulsion units were designed to improve the performance of submarines and take into account problems discovered during the operation of first-generation reactors. The designs included various modifications of the VM-4 reactor with different steam-generator units. Some reactors of the VM-4 class had a nominal power of 72 MWt (OK-300 steam generator units) others had a power of 90 MWt (OK-350, OK-700 steam generator units). Submarines of Project 670/Charlie class were equipped with one reactor. Others, like the nuclear powered submarines of the first generation, had two. The reactors were expected to be refueled after approximately eight years of service.[294]

The nuclear propulsion units installed in third-generation Soviet submarines are usually referred to as OKB-650, although there are several variations of the basic design.[295] They are rated at 190 MWt—almost twice the power of their VM-4 predecessors. Depending on the class, these submarines are equipped with one or two reactors. They are believed to use fuel with uranium enriched to 21–45%.[296]

The first submarines with third-generation nuclear reactors entered into service in 1980. As of 2017, a total of 43 third-generation submarines had been built. The first three Project 955 Borey ballistic missile submarines and the first Project 885 Yasen/Granay general-purpose submarine are equipped with upgraded third-generation reactors.

Development of the fourth-generation naval reactors began in the 1980s.[297] Known as KTP-6-85, the fourth-generation nuclear propulsion system is based on the KTP-6-185SP reactor with a power output of 200 MWt.[298] The first operational submarine equipped with the fourth-generation KTP-6-85 nuclear propulsion system will probably be the K-561 *Kazan*, a Project 885/Granay submarine that was laid down at the Sevmash plant in 2009.[299]

Light-water reactors are installed on all currently operational Russian submarines. As of April 2017, a total of 30 Russian nuclear submarines were operational and an additional 13 were in overhaul or repair and were expected to return to service. One submarine has been leased to India (see Table 7.1). In addition, thirteen submarines are at various stages of construction.[300]

Liquid metal-cooled submarine reactors

In the early days of the Soviet nuclear submarine program, a range of alternative reactor options were considered. These included a serious effort to use liquid-metal cooled (LMC) reactors with lead-bismuth alloy as the primary coolant. Their advantages included smaller size and lower weight compared to light-water reactors with the same power and other features that translated into better operability and performance.

The first submarine equipped with an LMC reactor was the K-27 of the Project 645/November class that entered service in late 1963 equipped with two 73 MWt RM-1 reactors.[301] Their fuel was made of a uranium-beryllium alloy with uranium enriched up to 90%.[302] However, its nuclear propulsion system suffered a serious accident in May 1968. Restoration was deemed unfeasible and the submarine never returned to service.

Notwithstanding the K-27 accident, it appeared possible to develop reliable and compact propulsion systems based on single liquid metal-cooled reactors. Two types were developed in the 1960s. The OKBM Design Bureau built the OK-550 unit, which was used in Project 705/Alfa submarines, while Gidropress developed the BM-40 unit for submarines of the Project 705K class (also known as Alfa). Both designs were rated at 155 MWt and delivered similar performance.[303]

Four Project 705/Alfa and three Project 705K/Alfa submarines equipped with liquid-metal cooled reactors entered service with the Soviet Navy between 1971 and 1981 and remained in service with the Northern Fleet until 1996. By 2013 all had been dismantled and their defueled reactor compartments had been put into storage at the Gremikha facility.[304] The reactor compartment of the K-123 was cut out and completely replaced after a serious accident in 1982. It was defueled and put in storage as well.[305]

Experimental nuclear submarines and reactors

The V-5 propulsion unit was designed in the 1960s as part of the effort to increase the maximum speed of Soviet nuclear submarines. Its design was later used as a prototype for all subsequent generations of propulsion units, including the OK-300, OK-350, OK-650, and their various modifications.[306] It was deployed on a one-of-a-kind submarine of the Project 661/Papa class. The experimental submarine, K-162 (colloquially known as "Golden Fish") had two light-water reactors on board, each delivering 177 MWt of power. It was accepted for service in 1969 and remained operational until 1989. The submarine was dismantled in 2010, but removal of spent fuel from the reactors was only completed in 2015.[307]

The VAU-6 auxiliary nuclear reactor unit was developed in an effort to improve the efficiency and stealth of diesel-powered submarines. It was installed in a separate unmanned compartment in the aft section of an upgraded diesel submarine.[308] The reactor, sometimes referred to as TVP-4, had a power of 5 MWt. The VAU-6 auxiliary unit was installed on a single submarine, the K-68 of the modified Project 651/Julliett class (Project 651E). After installation of the reactor, the K-68 remained on combat duty with the Northern fleet from 1986 to 1993. It was then decommissioned and dismantled.[309]

Other naval reactors

In the 1960s and 1970s the OKBM design bureau developed the KN-3 and OK-900B light-water integrated reactor units for surface military ships. These were second-generation naval reactors based on the design of the VM-4 nuclear submarine reactors. A total of five nuclear-powered military ships were built in the period between 1980 and 1998. KN-3 reactors were installed on four of them: heavy missile cruisers of the Project 1144/Kirov class (*Admiral Ushakov*) and Project 11442/Kirov class (*Admiral Nakhimov, Admiral Lazarev, and Pyotr Velikiy*). Each ship had two reactors rated at 300 MWt each. Two OK-900B reactors, each rated at 172 MWt, were installed in the *Ural* large reconnaissance ship of the Project 1941/Kapusta class.[310]

Between the late 1970s and mid-1990s, the Admiralty Shipyards in St. Petersburg built six nuclear-powered deep-diving mini-submarines, often referred to as "deep-diving stations" in Russian. These included three Project 1910 Kashalot/Uniform and three Project 1851 Nelma/X-Ray submersibles. According to some reports, each submarine is equipped with a single light-water 10 MWt reactor.[311] A number of reports and documents also mention a Project 10831 Kalitka/Norsub-5 deep-diving submarine, sometimes referred to as AS-12 Losharik.[312] The submarine, which was probably built in 2009–2010, is reportedly equipped with an E-17 nuclear reactor. There is virtually no information about the design of the reactors used in mini-submarines or the type of fuel they use.

The first nuclear icebreaker, *Lenin* of the Project 92 class, built in 1959, was equipped with three VM-A reactors with OK-150 steam generators and suffered the problems of early submarine reactors.[313] After a serious incident in 1966, the reactors were replaced with a second-generation OK-900 system, which consisted of two reactors. An improved OK-900A nuclear propulsion system was used on Project 1052 (*Arktika, Sibir,* and *Rossiya*) and Project 10521 (*Soviet Union* and *Yamal*) icebreakers, which entered into service during 1975–1985 and 1990–1993, respectively.

Improved single-reactor KLT-40 and KLT-40M power units were installed in *Sevmorput*, the world's largest icebreaker "lighter aboard" (barge transportation) ship, built in 1988, and in two reduced-draft icebreakers, *Taymyr* and *Vaygach*, built in 1989 and 1990 and designed for operation in the estuaries of Siberian rivers. Icebreaker reactors are normally refueled every four to six years.

Spent nuclear fuel management

In the early days of the Soviet nuclear-powered fleet, it was expected that refueling operations would be conducted by the navy at its own coastal facilities. To that end, in 1959–1962 the navy built three Coastal Technical Bases (CTBs), two for the Northern Fleet (Andreeva Bay and Gremikha), and one for the Pacific Fleet (Sysoyeva Bay in the Primorskiy Krai). Another base was later built for the Pacific Fleet at Gorbushechya Bay, Kamchatka.[314] Additionally, eight Project 326 Floating Technical Bases (FTBs) for reactor fuel reload operations were built from 1960 to 1966.

It soon became clear, however, that the navy did not have the necessary resources and expertise to handle such operations. To gain access to the reactor, which is situated in the lower part of the reactor compartment, technicians must first dismantle the equipment that sits above the reactor and then cut holes in the outer and main hulls approximately 6 by 4 meters in size. The complexity of the task required creating specialized units that would handle all fuel reload operations.[315]

Refueling operations were usually combined with repairs. The work on the hulls was done by the shipyard and refueling operations by mobile coastal technical base (CTB) brigades, using the equipment of the floating technical bases (FTB). The CTB crew opened up the reactor, unloaded spent fuel assemblies, performed required maintenance, loaded fresh fuel assembles into the reactor and then sealed and restarted it.

Reactors of the Northern Fleet submarines were refueled at the Zvezdochka and Sevmash facilities in Severodvinsk, the Navy's Ship Repair Plant (SRP) No. 10 in Polyarnyy, the Nerpa facility in Snezhnogorsk, and the Navy's SRP No. 35 in Murmansk. The Pacific Fleet boats were refueled at the Navy's SRP No. 30 (Chazhma Bay), the Zvezda facility in Bolshoy Kamen, and the Navy's SRP No. 49 (Seldevaya Bay in Kamchatka).[316]

After removal from a reactor, spent nuclear fuel assemblies were stored on the floating technical bases. Each Project 326 FTB ship could store up to 800 assemblies (reactors on first-generation boats contained approximately 200 assemblies). During 1971–1974 four FTBs were upgraded to Project 326M specifications. The upgrades included the use of special casks for handling spent nuclear fuel assembles, with each cask housing up to seven assemblies. As a result, the spent fuel capacity of the upgraded floating technical bases was reduced by 30%, to 560 assemblies.[317] During 1984–1990 the original floating bases were replaced by Project 2020 ships that are still in service today—the PM-65 and PM-12 in the Northern Fleet, and the PM-74 in the Pacific Fleet. The capacity of each Project 2020 ship is 1,400 spent fuel assemblies (or 204 casks, which is roughly equivalent to five spent fuel cores for third-generation nuclear submarine reactors).[318]

Removed fuel assemblies were transported to coastal technical bases for temporary storage. At the CTB facilities in Andreeva Bay and Sysoyeva Bay fuel was stored in concrete-lined pools. The Andreeva Bay site had a total capacity of 2,070 casks (equivalent to 80 spent reactor fuel cores for first-generation submarines). The Sysoyeva Bay facility could hold up to 549 casks (equivalent to 21 spent reactor fuel cores for first-generation boats). The base in Gremikha was equipped to store replaced removable components of liquid-metal cooled reactors and housed a pool that could hold 1,532 spent fuel assemblies of light-water reactors (eight first-generation reactor cores).[319]

The RT-1 reprocessing facility at the Mayak plant began operations in 1977 to reprocess naval as well as research and power reactor spent fuel. The first batch of naval spent fuel was delivered to Mayak from the Northern Fleet in 1973, before the facility was started. Spent fuel from the coastal technical bases at the Andreeva Bay and Gremikha was brought by ship to a navy storage facility in Murmansk, where it was loaded onto a special train that transported it to Mayak. The same trains were used to transport the spent icebreaker fuel. In 1993 the navy began to use trains for the transportation of spent fuel to the Mayak plant from the Atomflot storage facility in Severodvinsk as well.[320]

A similar arrangement was established for the Pacific Fleet. After temporary storage at the Sysoeva Bay coastal base, containers with spent fuel were brought by truck to the "54 km" site near the Dunay settlement, where they were loaded onto a special train. Spent fuel from the Gorbushechya Bay CTB in Kamchatka was shipped to Konyushkovo Bay, where it was loaded into containers, transported to the "54 km" site by truck, and brought the rest of the way to the RT-1 facility by train.

In 1982, a major radioactive leak was found at the Andreyeva Bay CTB, with radiation contaminating the environment. Urgent measures had to be taken to build new temporary storage facilities for spent fuel and to move fuel out of the damaged pools. The first new storage facility, which could hold 900 spent fuel casks in dry storage, became operational in June 1983. The second and third storage facilities, each holding 1,200 casks, became available between 1985 and 1986. All spent fuel from the leaking storage at the Andreyeva Bay CTB was moved to the new dry storage facilities. The new facilities were also used to store all spent fuel unloaded from nuclear submarines after 1984. The initial expectation was that these would be temporary facilities that would serve for three to four years. However, spent fuel has now been there for almost 30 years. Retrieving and transporting it to a processing plant has become problematic because some of the spent fuel assemblies have suffered corrosion damage.[321]

Other CTBs, which initially used pool-type storage facilities, ran into similar problems and could not accept new spent fuel beginning in the early 1990s. The floating technical bases were soon filled to capacity as well. The few trains that were available to transport spent fuel for reprocessing could not handle the volume of fuel from decommissioned submarines. As a result, by the early 1990s Russia was facing a very difficult situation with spent naval reactor fuel.

To deal with the situation, in April 1992 the Russian Navy authorized the creation of floating fuel reload facilities (FRFs), two at the Northern Fleet (in Olenya Guba and Severodvinsk) and one at the Pacific Fleet (in Bolshoy Kamen). These new facilities used most of the CTB and FTB infrastructure. After expansion, they managed to handle the bulk of the operations to unload spent fuel from decommissioned submarines.

In 1998, control over disposal of nuclear submarines and management of spent fuel and radioactive waste was transferred to Minatom. In 2000 it created two new units, SevRAO and DalRAO, which took over spent fuel and waste-management operations in the Northern Fleet and the Far East, respectively. The CTB storage facilities were absorbed by the new organizations, while the floating reload facilities continued to operate as separate entities.

Major progress in resolving various problems with spent naval reactor fuel management was made during 1998–2005. The old FTB ships were repaired and upgraded with new handling equipment, creating sufficient capacity to unload spent fuel from up to 18 submarines per year. Two new trains provided enough capacity to bring the number of spent fuel transport operations to 10–15 every year. In 2002, the Zvezdochka and Zvezda shipyards established new onshore facilities for handling spent nuclear fuel. New temporary storage depots were built at these shipyards, and at the former CTBs, to hold spent fuel containers prepared for shipment.

In 2014, Rosatom announced that it completed removal of the backlog of naval spent fuel from the Pacific Fleet.[322] Some spent fuel remains in the cores of damaged reactors in long-term storage. The situation is different in the Northern Fleet, where a significant backlog of spent fuel remains in storage.

An analysis of open data on submarine reloads suggests that naval storage facilities are still holding the equivalent of 145±30 cores of spent fuel unloaded from submarine and surface ship reactors.[323] Most of this spent fuel (about 100 cores) is held in dry storage compartments at Andreeva Bay. A significant portion of that fuel appears to be damaged and, therefore, will require special handling. The removal of spent fuel from the dry-storage compartments in Andreeva Bay will begin in June 2017.[324] The rest of the spent fuel from light-water reactors is held on floating technical bases and technological vessels; in dry storage compartments at the DalRAO facility in Sysoyeva Bay; and in special containers at the RTP Atomflot, DalRAO, and Zvezda facilities.

In 2012, Rosatom began removal of the fuel sections of the core of liquid-metal cooled reactors stored at Gremikha (spent fuel of light-water reactors has been already removed from the site). They are currently being placed into temporary storage at an RTP Atomflot depot and awaiting transfer to the RT-1 facility for processing, which is expected to begin in 2016.[325] Removal of all fuel from Gremikha is expected to be completed around 2027.[326]

A number of reactors were lost in submarine accidents or disposed of at sea (fueled as well as de-fueled). Some reactors were also placed in long-term storage with spent nuclear fuel inside.

The first nuclear-powered submarines had the largest number of accidents, most of them reactor-related:

- Two Project 627A/November class submarines were lost at sea with fuel in their reactors. The K-8 submarine was lost in 1970 after a fire on board in the Bay of Biscay. In 2003, K-159 sank in the Barents Sea as it was towed to dismantlement.
- Two reactor compartments with spent fuel inside were dumped in the Abrosimova Bay near Novaya Zemlya after accidents: the K-11 submarine of the Project 627A/November class (accident in 1965, fuel removed from one reactor) and the K-19 submarine of the Project 658/Hotel class (accident in 1961).
- Three-compartment sections of two submarines of the Project 675/Echo II class—K-116 and K-431—were placed in long-term storage with spent fuel inside three of the four reactors.

- Two reactor compartments, of the K-3 Project 627/November and K-5 Project 627A/November submarines, were dumped in the Abrosimova Bay after spent fuel was removed from the reactors.[327]

Second-generation reactors proved to be more reliable and the number of accidents was significantly reduced. One submarine, K-140 of the Project 667A/Yankee class, had one of its reactors replaced after an accident in 1971. The damaged reactor was scuttled near Novaya Zemlya with its spent fuel inside.[328] Another submarine of this class, K-219, was lost in the Atlantic in 1986 after a missile explosion on board. The three-compartment section of the K-314 submarine of the Project 671/Victor I class, which suffered a serious accident in 1985, was put in long-term storage with nuclear fuel inside the reactor.[329]

Two submarines of the third-generation types were lost to non-reactor-related accidents. In April 1989, the K-187 *Komsomolets* sank in the Norwegian Sea after a fire on board. The K-141 *Kursk*, was lost in the Barents Sea in 2000 after an explosion in the torpedo compartment. The *Kursk* was raised in 2001 and later dismantled.

In 1981, the reactor compartment of the K-27 of the Project 645/November class, equipped with two RM-1 liquid-metal cooled reactors still containing nuclear fuel, was sealed off and the submarine was scuttled in Novaya Zemlya's Abrosimova Bay.

There were two accidents with the first reactors installed on the *Lenin* icebreaker. After the first one that took place in 1965, damaged spent fuel from one of the reactors was placed in a special container and dumped in Novaya Zemlya's Tsivolki Bay in 1967. The second accident took place in 1967. Following the accident, the entire icebreaker's reactor compartment with de-fueled reactors, was scuttled at the Tsivolki Bay.[330]

HEU consumption in naval reactors[331]

Naval reactors are likely to remain a major factor in the use of highly-enriched uranium in Russia. There has been virtually no discussion of a possible conversion of naval reactors to LEU and it appears that the new submarines that will enter into service in the coming years will continue to use HEU fuel, preserving the status quo for decades. The example of the RITM-200 reactor designed for the new class of icebreakers, suggests that some types of naval reactors can be converted to LEU fuel. It is not clear, however, that the designers have strong incentives to do so.

The data on the number of refueling operations conducted by the Soviet and Russian Navy, combined with information about submarine construction, allows an estimate to be made of the historical consumption of HEU in the reactors of submarines as well as in military surface ships and civilian vessels. It also allows projections to be made of the HEU demand for the next decade. However, it should be noted that this estimate carries a large uncertainty, primarily due to the lack of reliable information about the type of fuel used in naval reactors and the fuel's HEU content.

The very first naval reactors appear to have used LEU fuel with an enrichment of about 6%. However, it seems that by the early 1960s the first-generation reactors were loaded with fuel containing 20% enriched uranium. The uranium content of first-generation reactor cores could also vary from 30 kg to 50 kg of uranium-235.[332] This estimate assumes that fresh fuel in first-generation reactors contained, on average, about 50 kg of uranium-235 in 250 kg of 20% HEU.

The second-generation reactors are believed to use fuel with 21% enrichment, although some may have used fuel with higher enrichment as well. For the purposes of this estimate, we assume that a reactor core contains about 600 kg of 21% enriched uranium or about 120 kg of uranium-235.[333]

Third-generation reactors are believed to use fuel with a higher enrichment, ranging from 21% to 45%. Each core is believed to contain about 200 kg of uranium-235.[334] Given that the average enrichment of uranium in third-generation reactors is reported to be about 33%, each core is assumed to contain about 300 kg of uranium with 21% enrichment and 300 kg of 45% HEU.

There is no reliable information on the enrichment or the uranium content of fourth-generation reactors. However, it appears that these characteristics are not substantially different from those of the third-generation reactors.

Since the reactors installed on military surface ships are based on the VM-4 second-generation submarine design, they are assumed to use the same type of fuel and the same amount of HEU in the reactor core.

Liquid-metal cooled reactors installed on submarines used 90% enriched fuel. The first reactors, RM-1, are believed to have contained 90 kg of uranium-235. Subsequent designs, the VM-40A and OK-550, used about 200 kg of uranium-235 in their cores.[335]

As for the civilian ships, the OK-900 class reactor cores use fuel with uranium enriched to 36% and 60%.[336] One core is assumed to contain about 200 kg of 36% HEU and 100 kg of 60% HEU.[337] The KLT-40 class reactors are believed to use 90% HEU fuel. Each core is estimated to contain about 150 kg of HEU.[338]

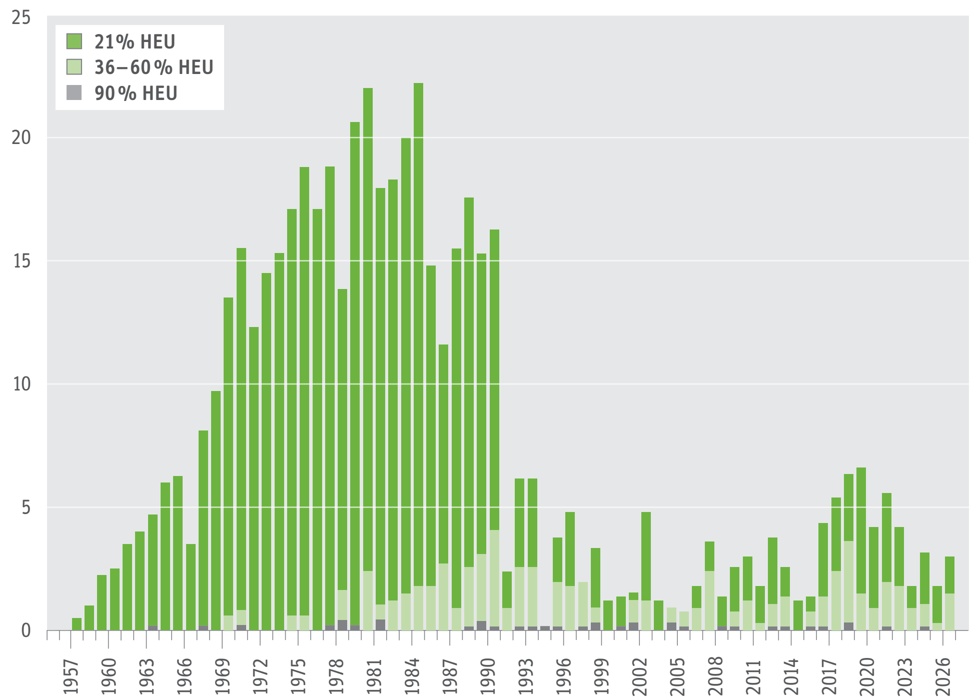

Figure 7.4. Estimated annual HEU consumption in naval reactors (tons of HEU).

Using these assumptions, it can be estimated that, as of the end of 2016, Soviet and Russian naval nuclear reactors had consumed about 113 tons of uranium-235 in HEU, with enrichments ranging from 21 to 90%.[339] The actual amount of HEU used is estimated to be 490 tons. Most of this material, about 430 tons, however, was HEU with an enrichment of 21%. Figure 7.4 shows the estimated consumption of HEU of different enrichments in naval reactors.

Most of the naval HEU—about 100 tons of uranium-235—was consumed by submarine reactors; civilian ships consumed an estimated 12.5 tons of uranium-235; and surface military ships account for about 1.2 tons of uranium-235 in their fuel.

The data about the current status of Russia's fleet of submarines and nuclear-powered military surface ships suggest that, in the coming ten years, Russia will produce HEU fuel for about 68 new reactor cores. Of these, 22 will be for reactors of second-generation submarines and surface ships and 46 for third- and fourth-generation submarines. The historical refueling rate for icebreakers suggests that Russia will need to produce about ten cores for reactors of the OK-900 type and probably five for KLT-40 reactors.

Taken all together, the above estimates suggest that, in the next ten years, Russia is likely to use about 14 tons of uranium-235 in 46 tons of HEU of various enrichments, corresponding to an annual consumption of about 4.6 tonnes of HEU. Taking into account that more than half of this material is believed to be 21% HEU, this corresponds to about 16 tons of 90% HEU equivalent over ten years or 1.6 tons of 90% HEU annually.

Icebreakers would account for average annual consumption of about 380 kg of HEU with enrichment in the 36–90% range (about 230 kg 90% HEU equivalent), while the remaining 4,200 kg of HEU, with the enrichment in the 21–45% range (corresponding to about 1,300 kg of 90% HEU equivalent), will be consumed by reactors on submarines and military surface ships. Most of this HEU fuel, an equivalent of 940 kg of 90% HEU annually, will be handled by the enterprises at Severodvinsk and by the reloading facilities of the Northern Fleet.

Even though Russia has a large stock of HEU that was produced for its weapon program, it appears that it does not rely on its weapon stock to produce HEU for naval reactors. Russia has made a commitment to stop production of HEU for nuclear weapons, but this pledge apparently does not cover production of HEU for non-weapon military purposes, such as naval reactors.

7A APPENDIX
Russia's nuclear submarine fleet

Nuclear-powered submarines

Nuclear submarines of the Russian Navy are usually divided into three categories according to their role and the weapons they carry. Nuclear submarines with ballistic missiles (PLARB or SSBNs) are part of Russia's strategic nuclear deterrent. Nuclear submarines with anti-ship cruise missiles have a primary mission of countering aircraft-carrier groups (PLARK or SSGNs). All other submarines are usually referred to simply as PLA (nuclear submarine). These include multipurpose and torpedo submarines that can be used in a variety of roles and against a range of targets—surface ships and submarines or targets on land. Special-purpose submarines are normally considered separately from these three main categories.

As of April 2017, the Russian Navy included 42 nuclear-powered submarines, listed in Table 7.1. Submarines in active service, in overhaul, reserve, and under construction. le 7.1. This number includes 13 ballistic missile submarines and 27 cruise missile and multipurpose submarines. It also includes two special-purpose submarines, but not the seven deep-diving submersibles, which are described in a separate section. Twenty-seven submarines are assigned to the Northern Fleet and 16 submarines to the Pacific Fleet. The table also includes 13 submarines that are under construction, as well as the submarine leased to India, which are not included in the total of 42 submarines.

Submarine	Entered service	Comments
Project 667BDR/Delta III		
K-223 Podolsk	1979	Pacific Fleet
K-433 Svyatoy Georgiy Pobedonosets	1980	Pacific Fleet
K-44 Ryazan	1982	Pacific Fleet
Project 667BDRM/Delta IV		
K-51 Verkhoturye	1984	Northern Fleet
K-84 Yekaterinburg	1985	Northern Fleet
K-114 Tula	1988	Northern Fleet. In overhaul since December 2014. Expected to return in 2017.
K-117 Bryansk	1988	Northern Fleet. Expected to enter overhaul in 2017.
K-18 Karelia	1989	Northern Fleet
K-407 Novomoskovsk	1990	Northern Fleet
Project 941/Typhoon		
TK-208 Dmitry Donskoy	1981	Northern Fleet. Test platform for Bulava SLBM.

Project 955 Borey		
K-535 Yuri Dolgorukiy	2012	Northern Fleet
K-550 Alexander Nevskiy	2013	Pacific Fleet
K-551 Vladimir Monomakh	2014	Pacific Fleet
Knyaz Vladimir		Construction started in 2012
Knyaz Oleg		Construction started in 2014
Generalissimuss Suvorov		Construction started in 2014
Imperator Alexander III		Construction started in 2015
Knyaz Pozharskiy		Construction started in 2016
Project 949A/Oscar II		
K-119 Voronezh	1989	Northern Fleet
K-410 Smolensk	1990	Northern Fleet
K-266 Orel	1992	Northern Fleet
K-132 Irkutsk	1988	Pacific Fleet. In overhaul since 2001.
K-442 Chelyabinsk	1990	Pacific Fleet. In overhaul since 2014.
K-456 Tver	1992	Pacific Fleet
K-186 Omsk	1993	Pacific Fleet
K-150 Tomsk	1996	Pacific Fleet
Project 971 Shchuka B/Akula		
K-317 Pantera	1990	Northern Fleet
K-461 Volk	1991	Northern Fleet. In overhaul since 2014.
K-328 Leopard	1992	Northern Fleet. In overhaul since 2011.
K-154 Tigr	1993	Northern Fleet
K-157 Vepr	1995	Northern Fleet. In overhaul since 2012.
K-335 Gepard	2001	Northern Fleet
K-322 Kashalot	1988	Pacific Fleet. In overhaul since 2003.
K-331 Magadan	1990	Pacific Fleet. In overhaul since 2012.
K-391 Bratsk	1989	Pacific Fleet. In overhaul since 2003.
K-419 Kuzbass	1992	Pacific Fleet
K-295 Samara	1995	Pacific Fleet. In overhaul since 2014.
K-152 Nerpa	2009	Leased to India
Project 945/Sierra		
B-239 Karp	1984	Northern Fleet. In reserve and overhaul since 1994.
B-276 Kostroma	1987	Northern Fleet. In overhaul since 2015.
Project 945A/Sierra		
B-534 Nizhny Novgorod	1990	Northern Fleet
B-336 Pskov	1993	Northern Fleet
Project 671RTMK/Victor III		
B-414 Daniil Moskovskiy	1990	Northern Fleet
B-138 Obninsk	1990	Northern Fleet
B-448 Tambov	1992	Northern Fleet. In overhaul since 2011.

Project 885/Granay		
K-560 Severodvinsk	2014	Northern Fleet
K-561 Kazan		Construction started in 2009. Expected to enter service in 2017–2018.
K-573 Novosibirsk		Construction started in 2013
Krasnoyarsk		Construction started in 2014
Arkhangelsk		Construction started in 2015
Perm’		Construction started in 2016
Ulyanovsk		Construction started in 2017
Project 09786/Delta III Stretch		
KS-129 Orenburg	1981	Northern Fleet
Project 09787/Delta IV Stretch		
BS-64 Podmoskovye	1986	Northern Fleet
Project 09852		
Belgorod		Construction started in 2012. Being converted from a Project 949A/Oscar II submarine.
Project 09851		
Khabarovsk		Construction started in 2014

Table 7.1. Submarines in active service, in overhaul, reserve, and under construction.

Ballistic missile submarines

Project 667BDR/Delta III. As of 2017, there were three active ballistic missile submarines of the Project 667BDR/Delta III class in the Pacific Fleet. Even though these submarines, built from 1979 to 1982, are among the oldest in the fleet, Russia has invested considerable effort to keep them in service. In February 2017, K-44 *Ryazan,* returned to service after a six-year overhaul that included the refueling of its nuclear reactors.[340] The submarines periodically go on combat patrol missions and take part in exercises that involve test launches of their ballistic missiles. However, they are likely to be withdrawn from service within the next 5–10 years.

Project 667BDRM/Delta IV. As of 2017, the Northern Fleet operated five Project 667BDRM/Delta IV ballistic nuclear missile submarines. These boats entered into service during 1984–1990. In the mid-1990s to early 2010s they all underwent repairs and refueling of their nuclear reactors at the Zvezdochka plant. Normally, a submarine’s service life is extended by five to ten years at a time, which means that Project 667BDRM/Delta IV submarines will remain in service until at least 2016–2022. It is likely that their service life will be extended further. The sixth submarine, K-114 *Tula*, is in overhaul at the Zvezdochka plant with the work to be completed in 2017.[341] K-117 *Bryansk* is scheduled to begin overhaul after that.[342]

Project 941/Typhoon. The Northern Fleet also operates the TK-208 *Dmitry Donskoy*, the only Project 941/Typhoon class ballistic missile submarine still in active service, as a launch test platform for the new Bulava submarine-launched ballistic missile (SLBM). The submarine also takes part in trials to detect the sound signatures of new and upgraded nuclear submarines.[343] Two other submarines of this class, the TK-17 *Arkhangelsk* and the TK-20 *Severstal*, were mothballed in 2004, and are awaiting dismantlement.[344]

Project 955 Borey. As of April 2017, Russia had three new Project 955 Borey class boats armed with Bulava SLBMs. The lead ship of this class, *Yuri Dolgorukiy*, serves with the Northern Fleet, whereas *Alexander Nevskiy* and *Vladimir Monomakh* have been transferred to the base in Vilyuchinsk, Kamchatka. The armament program calls for construction of five more, which are currently at different stages of construction.[345]

Multipurpose and cruise missile nuclear submarines

Project 949A/Oscar II. Submarines of this class carry cruise missiles that are designed to counter aircraft carrier groups. Of the total of eleven Project 949A/Oscar II submarines that have been built, eight remain in service. Three are based with the Northern Fleet, and five serve with the Pacific Fleet. The submarines, which were built during 1988–1996, are undergoing overhauls that will keep them in service for the next several years, but are approaching the end of their service lives.

The K-119 *Voronezh* and K-410 *Smolensk* in the Northern Fleet underwent overhaul at the Zvezdochka plant in 2006–2011 and 2011–2013, respectively. The K-266 *Orel* was delivered to Zvezdochka for repairs in November 2013 and returned to the Navy in 2017.[346] The overhaul extends the service life of a submarine by three and a half years.[347]

Of the five Project 949A submarines in the Pacific Fleet, three—the K-186 *Omsk*, the K-150 *Tomsk*, and the K-456 *Tver*—were in active service in 2017. The K-442 *Chelyabinsk* and the K-132 *Irkutsk* are expected to return to service in 2018 and 2019, respectively.[348]

Project 971 Shchuka B/Akula. These are multipurpose submarines that carry cruise missiles and torpedoes. Of the eleven submarines of this class that are formally in service with the Russian Navy, six are assigned to the Northern and five to the Pacific Fleet. In addition, in 2012, the K-152 *Nerpa* was leased to India, where it is known as INS *Chakra*.

As of April 2017, only two or three of the six Project 971/Akula submarines with the Northern Fleet were in active service—the K-317 *Pantera*, the K-335 *Gepard* and the K-154 *Tigr*, which is reportedly awaiting a medium overhaul. The others are at various stages of overhaul. Some were scheduled to return to service in 2015–2017, but the return was clearly postponed. The overhaul, which may include installation of new missiles and a refurbishment of nuclear reactors, has taken longer than expected.

Of the five Project 971/Akula submarines of the Pacific Fleet, two were undergoing repairs in the Far East and two, *Bratsk* and *Samara*, were transferred for repairs to the Zvezdochka plant in Severodvinsk in 2014. These submarines are expected to return to service around 2018.[349] After its overhaul is completed, one, the K-322 *Kashalot*, may be leased to India, where it would join the K-152 *Nerpa*.[350]

Project 945 and Project 945A/Sierra. The Northern Fleet has four Project 945 Barrakuda/Sierra I and Project 945A Kondor/Sierra II class titanium-hull multipurpose nuclear submarines, built during 1983–1992. As of 2017, however, only the two submarines of the Proejct 945A class, the B-234 *Nizhniy Novgorod* and the B-336 *Pskov*, were in active service. The B-336 Pskov completed repairs and returned to service in 2015.[351] Two Project 945 submarines, the B-239 *Karp* and the B-276 *Kostroma*, were expected to return to service in 2017, even though reports indicate that the overhaul of *Karp*, which has been out of service since 1994, has been suspended.[352]

Project 671RTMK/Victor III. Multipurpose nuclear submarines of the Project 671RTMK Shchuka/Victor III class are among the few second-generation submarines remaining in service. There are three submarines of this class, all of them assigned to the Northern Fleet. As of 2017, two, the B-138 *Obninsk* and the B-414 *Daniil Moskovskiy*, were in active service, although the latter appears to be kept at a pier.[353] The B-448 *Tambov* was moved to the Nerpa plant in 2011 for an overhaul. According to some reports, the Russian Navy decided against upgrading any of the remaining Project 671RTMK submarines, so it is possible that the remaining active submarines will be withdrawn from service.[354] Since the B-138 *Obninsk* has just completed a medium overhaul, it will probably remain in service longer than other submarines of this class.[355]

Project 885 Yasen/Granay. The old cruise-missile and multipurpose submarines that are approaching the end of their service lives will be replaced by new submarines of the Project 885 and Project 885M class (known as Yasen in Russia and Granay in the West). Construction of the lead submarine of this class, the K-560 *Severodvinsk*, began in December 1993, but, for a number of reasons (primarily budgetary), construction was not completed until 2014, when the submarine finally joined the Northern Fleet.

The current plan calls for construction of seven submarines of this class. The second and the subsequent submarines are built as Project 885M Yasen-M class boats—a modification that reportedly includes a new fourth-generation nuclear reactor. Because of the high cost of the construction, the Russian Navy considered limiting the production run to four to six hulls.[356] In the end, however, the original plan appears to be unchanged. As of 2017, four submarines were at various stages of construction at the Sevmash plant—K-561 *Kazan*, K-573 *Novosibirsk*, *Krasnoyarsk*, and *Arkhangelsk*.[357] *Kazan* was laid down in 2009 and was moved from covered dock in March 2017. It is expected to enter service in 2017–2018.[358] *Arkhangelsk* was laid down in March 2015 and may join the fleet by 2020. One more submarine, *Perm'*, was laid down on July 29, 2016.[359]

Nuclear powered special purpose submarines

The Russian Navy also operates nuclear powered submarines as mini-submarine carriers.

The KS-129 *Orenburg* was converted to a Project 09786/Delta III Stretch-class carrier of mini-submarines. The conversion was completed in 2003 and the submarine was assigned to the Northern Fleet. The status of this submarine is uncertain. While it was said to be prepared for retirement after 2012, some reports suggest that it was operational as late as 2015.

One of the Project 667BDRM/Delta IV submarines, the BS-64 *Podmoskovye*, has been converted into a special-purpose carrier of mini-submarines at the Zvezdochka facility. The submarine has been in dry dock since 1999. In December 2016 it was handed over to the Northern Fleet.[360]

The construction of the twelfth submarine in the Project 949A class, *Belgorod*, began in 1992, but it was put on hold in 2009 when the boat was 85% complete. It is believed that it will be completed as a special-purpose submarine of the Project 09852 class, which was formally laid down at the Sevmash plant in December 2012.[361] In July 2014, Sevmash began construction of another special-purpose submarine, the *Khabarovsk* of the Project 09851 class.[362]

Nuclear deep submersible stations

As of 2017, the Russian Navy was believed to operate seven nuclear-powered deep-diving submersible vehicles. They are assigned to a Northern Fleet division that is directly subordinated to the Main Directorate for Deep-Water Research of the Ministry of Defense (GUGI MO in Russian).[363] Information about the status of deep-diving submarines (see Table 7.2) is scarce and often unreliable. Three of the Project 1910/Uniform class submersibles are believed to be formally in service, although two of them, the AS-13 and AS-15, appear to be undergoing repair at the Zvezdochka plant.[364] Of the three Project 1851/X-Ray deep-diving stations that are believed to be in service, one, the AS-23, was reported to be under repair at the Zvezdochka plant.[365] It cannot be ruled out that some of the submarines of these types have already been decommissioned and eliminated. A newer deep-submersible station, known as the AS-12 “Losharik,” of the Project 10831/Norsub-5 class, is believed to have been in operation since 2010 and completed an overhaul in 2014.[366]

Submarine	Entered service	Comments
Project 1910/Uniform		
AS-13	1986	Status uncertain. May be in overhaul or dismantled.
AS-15	1991	Appears to be in overhaul
AS-33	1994	Believed to be operational
Project 1851/X-Ray		
AS-23	1986	In overhaul
AS-21	1991	Believed to be operational
AS-35	1995	Believed to be operational
Project 10831/Norsub-5		
AS-12	2010	Believed to be operational

Table 7.2. Deep-diving submersible vehicles.

Military nuclear-powered surface ships

As of 2017, only the *Pyotr Velikiy*, the last of the three Project 11442/Kirov class cruisers, was still in service with the Northern Fleet. It is expected to undergo an overhaul in 2018–2021.[368] The *Admiral Nakhimov*, also assigned to the Northern Fleet, was withdrawn from active service in 1999. In 2013, Sevmash began an overhaul of *Admiral Nakhimov* that is scheduled to be completed in 2019.[369] According to current plans, the *Ural*, which was based in the Pacific, and the *Admiral Ushakov*, which served with the Northern Fleet, will be dismantled. Spent fuel has been removed from both ships.[370] The reactor of the cruiser *Admiral Lazarev*, which served with the Pacific Fleet, was defueled in 2005, but no decision has been made as to whether to return the ship to service.[371] It appears likely that it will be dismantled.[372]

Also, Russia's Navy is considering commissioning a new nuclear-powered destroyer of the Project 23560 Leader. The Severnoye Design Bureau was requested to design both nuclear and gas-turbine-powered versions, but the nuclear version appears to be the only one currently under consideration.[373]

Ship	Entered service	Comments
Project 1144/Kirov		
Admiral Ushakov	1981	Northern Fleet. Withdrawn from service in 1997. Awaiting dismantlement.
Project 11442/Kirov		
Admiral Nakhimov	1988	Northern Fleet. Withdrawn from active service in 1999. Defueled. Expected to return to service in 2019.
Admiral Lazarev	1984	Pacific Fleet. Withdrawn from active service in 1999. Defueled. Likely to be dismantled.
Pyotr Velikiy	1998	Northern Fleet. In active service.
Project 1941/Kapusta		
Ural	1988	Pacific Fleet. Withdrawn from service in 1989. Fuel removed in 2009. Will be dismantlement in 2019.

Table 7.3. Status of military nuclear-powered surface ships as of 2017.

Civilian nuclear-powered ships

Table 7.4 shows the current status of Russia's nuclear-powered civilian fleet.[374] Six nuclear-powered ships had been decommissioned by early 2015, including two nuclear-powered icebreakers that are being kept in reserve. By 2021, all but one of these icebreakers, the *50 Let Pobedy*, will have reached the end of their service lives.

Name	Entered service	Fuel reloads	Comment
Project 92			
Lenin	1959	6	Decommissioned in 1990. Spent fuel removed.
Project 1052			
Arktika	1975	7	Decommissioned in 2008. Spent fuel removed.
Sibir	1978	6	Decommissioned in 1993. Spent fuel removed.
Rossiya	1985	4	Decommissioned in 2013. Spent fuel removed.
Project 10081			
Sevmorput	1988	4	Returned to service in 2015
Project 10580			
Taymyr	1989	6	To retire after 2020
Vaygach	1990	6	To retire in 2022
Project 10521			
Sovetskiy Soyuz	1989	3	In reserve since 2007. Expected to return to service in 2018. Fuel removed.
Yamal	1992	3	To retire in 2020
50 Let Pobedy	2007	1	To retire after 2025
Project 22220			
Arktika			Laid down in 2013. Expected to enter service in 2017.
Sibir			Laid down in 2015
Ural			Laid down in 2016

Table 7.4. Current status of the Russian nuclear-powered civilian fleet.

The *Sovetskiy Soyuz* is expected to return to service in 2018.[375] The *Sevmorput* returned to service in 2015, after undergoing an overhaul and refueling.[376] The first icebreaker, *Lenin*, has been cleaned out and converted to a museum in Murmansk. The other decommissioned nuclear icebreakers are in "cold storage." The federal program "Nuclear and Radiation Safety in 2016–2020 and until 2025", calls for dismantlement of two icebreakers—the Project 1052 class *Sibir* and *Arktika*.[377]

On November 5, 2013 the Baltic Shipyard laid down a keel of the first Project 22220 nuclear icebreaker, known as the LK-60 *Arktika*, to be completed by 2018. Rosatom plans to build two more ships of the same type, the Project 22220 class *Sibir* and *Ural*, by 2019 and 2020, respectively. As of early 2015, the shipyard had contracts for two ships, but the construction of reactor components for three icebreakers was already underway.[378] The icebreakers will be equipped with the RITM-200 integrated nuclear propulsion unit, which includes two 175 MWt reactors. The reactors are expected to use LEU fuel with an enrichment of just below 20%.[379]

8 CONCLUSION
Prospects for HEU minimization in Russia

Challenges to the HEU minimization effort

Probably the most serious challenge for the HEU minimization effort in Russia is the fact that the technical community of the Russian nuclear industry does not seem to see the need to reduce the use of the material in domestic applications. Although Russia has repeatedly stated its commitment to strengthening the security of vulnerable fissile materials and has participated in a number of programs aimed at reducing the use of HEU, minimization has never been adopted as a practical guiding principle in the activity of its nuclear enterprise.

Support from the nuclear industry, namely Rosatom, would be particularly important, since historically it has been a strong and independent institution largely responsible for setting its own policies in all matters that deal with the structure and strategic direction of the enterprise as well as with production, use, and disposition of fissile materials. This power, as well as the lack of external actors with comparable influence and expertise, has allowed Rosatom to shape virtually all policies regarding its activities and block those decisions that do not have its support. The key role of Rosatom's predecessor agency was demonstrated in the decision to begin conversion of Soviet-origin research reactors abroad. This program, as well as the effort to repatriate Soviet-origin HEU fuel, is still supported by Rosatom (see Chapter 4). It is one of the few programs that have survived the recent decision to stop most of the U.S.-Russian nuclear security cooperation. At the same time, the Russian reactors conversion program, which did not seem to have strong Rosatom support, has been effectively terminated.

There are several possible explanations for the lack of support for HEU minimization within Rosatom. One is pure inertia. Maintaining the status quo is the default option while, in almost all cases, changing the policy would require a dedicated and often costly effort normally requiring strong political or economic incentives. Until recently, international assistance and cooperation programs in Russia provided strong political and economic inducements that supported the nuclear security programs and some HEU minimization activities. These incentives largely disappeared at the end of 2014, however, when Russia withdrew from most cooperation programs.

In the absence of external factors, there is little internal political pressure that would force Rosatom to place HEU minimization among its priorities. Justifiably or not, the industry appears to be confident in the adequacy of the security for the fissile materials in its custody and it is extremely difficult for other institutions to challenge that confidence. The political leadership most likely relies on Rosatom's assessment of most nuclear security issues. Russian security services may not have the expertise and understanding that would allow them to properly evaluate the threat posed by circulation of HEU, let alone take the lead in addressing the issue. Regulatory oversight is also not sufficiently strong. Rosatom is responsible for regulatory oversight of most of its own defense-related activities and the civilian body, Rostekhnadzor, does not have the institutional power to match that of Rosatom.

Indeed, Rosatom's political considerations probably work against the HEU minimization effort. Rosatom's main priorities are maintaining the nuclear weapons complex and supporting development of the nuclear power industry, especially in those areas where Russia can claim a leadership position, such as in the development of fast-neutron power reactors. Some of these missions use existing HEU facilities and, even in those areas where HEU is not essential, a conversion effort would distract from the organization's primary mission.

Another political priority for Rosatom is the environmental cleanup of the legacy of radioactive waste that it inherited from the Soviet nuclear program. This is a highly visible mission that enjoys both governmental and public support.[380] Although the implementation of the program has resulted in the closure of some research facilities and the clean-out of a number of sites, including ones that used HEU, HEU minimization is not systematically addressed.

There are also few internal economic incentives to minimize the use of HEU. Although operators of HEU facilities may bear some additional costs associated with more stringent physical security and material accounting and control requirements, these costs do not seem to be sufficiently high to encourage them to consider HEU removal. Also, in the absence of a targeted industry-wide program that would cover the cost of LEU fuel development and reactor conversion, few operators find conversion economically affordable.

Another problem that complicates development of a viable HEU minimization program is uncertainty about what would be the scope of the effort. As described earlier in this section, the largest users of HEU in Russia are its naval, breeder, and tritium production reactors. Although the continuing use of HEU in these applications should not prevent an effort to reduce the amount of HEU elsewhere, a comprehensive HEU minimization effort would have to take these activities, and the HEU flows associated with them, into account. In Russia, civilian and defense-related flows of HEU are tightly integrated in the areas of fuel fabrication, fuel development and testing and transportation. An HEU minimization program with a narrow focus on civilian applications or on civilian research reactors would bring benefits by removing some material from some sites, but one can see how the limited impact of such a program would weaken its rationale.

At this time, there appears to be no clear path toward reducing the use of HEU in the applications that consume the largest amounts of the material. The BN-600 will probably continue to use HEU fuel and may have its license extended when it expires in

2020. The newer BN-800 reactor is mostly plutonium fueled, but is currently using HEU in about a third of its core. Unlike the United States, which has shifted to producing its tritium in LEU-fueled power reactors, Rosatom appears to be committed to continuing tritium production in dedicated HEU-fueled reactors. There is no reason to expect that the new reactor that will replace *Rusla*n and LF-2 in 2023 will use LEU fuel. Finally, while Russia is moving to LEU fuel in its new generation of nuclear-powered icebreakers, there has been no indication that it may consider switching to LEU in submarine reactors. Indeed, there is no clear route that would allow an informed discussion of this issue.

Practical steps toward reducing the use of HEU

Even though there is no simple solution that would restart HEU minimization programs in Russia, there are a number of possibilities for making progress in specific areas and for creating conditions that will encourage Russia to become an active participant in the continuing international effort to reduce the use of HEU.

This effort should focus on securing the support of technical experts in the Russian nuclear industry, since it plays a key role in shaping Russian state policies on nuclear security and the use of fissile materials. While Russia supports the U.S.-led effort to secure fissile materials in general, it does not necessarily share the view that minimization of HEU use in Russia is an essential part of that effort. To some extent, this position reflects the lack of an internationally agreed upon strategy for dealing with HEU or a process that would develop such a strategy. Ideally, Russia would participate in this discussion on the technical, as well as on the political, level. To get Russia involved, however, the international community should develop a strong case for HEU minimization that would take into account all aspects of the problem, from nuclear security to nonproliferation and nuclear disarmament, and that would appeal to the Russian technical community.

The HEU minimization program that exists today is largely an extension of the U.S. program to secure most vulnerable fissile materials worldwide. Although it has been an extremely valuable and productive effort, it left little room for other countries to participate in shaping the goals and key elements of the program. Also, it does not cover some important uses of HEU, which certainly limits its reach and undermines its effectiveness.

Some progress on getting an internationally approved HEU strategy has been made in the context of the U.S.-led Nuclear Security Summit process. However, the strongest commitment to HEU minimization achieved there merely encouraged states "to minimize their stocks of HEU […] as consistent with national requirements" and "to continue to minimise the use of HEU through the conversion of reactor fuel from HEU to LEU, where technically and economically feasible."[381] Overall, although the summit process has helped make some progress toward reducing the use of HEU, it did not become a forum in which a strategic vision for HEU minimization could be discussed or that ensured that key countries have a significant stake in this effort. Indeed, an attempt to include a discussion of HEU guidelines in the 2014 summit agenda proved unsuccessful. On top of that, in 2014 Russia pulled out of the summit preparation process, further reducing the chances of the 2016 Summit becoming an effective channel for consultations on this and other nuclear security issues.[382]

The Nuclear Security Summit commitment to reduce the use of HEU could potentially cover all reactors fueled with HEU. In practice, however, it has been applied primarily to civilian HEU use. The only HEU minimization effort being implemented, the U.S. M³ program (formerly GTRI), is in practice limited to this scope. It explicitly excludes important applications, such as naval reactors. But even within its scope, the M³/GTRI program has not yet produced an international consensus on the need to completely eliminate HEU from civilian research. The United States and Europe are likely to continue to use HEU in at least a few civilian research reactors for decades to come. This leaves Russia in a position to argue that its policy toward civilian uses of HEU is in line with the generally accepted practice, even if the number of HEU reactors it operates is considerably larger than in any other country. A clear policy on high-performance research reactors may help better define priorities for the minimization effort and encourage earlier shutdown of non-essential facilities.

It is difficult to expect that an international HEU minimization strategy would be able to reach an agreement on facilities and reactors outside of the civilian domain, such as defense-related research reactors and critical assemblies. These issues have to be taken into account, however, as they can directly affect decisions regarding the overall approach to minimization. It is particularly important in Russia, where the line between civilian and defense-related facilities is often difficult to draw and where a focus on civilian facilities is unlikely to bring a significant change in the nuclear security environment.

Despite the lack of a comprehensive approach to HEU, the U.S.-led minimization program has already made remarkable progress. As of October 2015, all HEU has been removed from 29 countries and Taiwan. Work continues to remove the material from other countries that operate HEU reactors. Most importantly, the U.S. activities have established a set of de facto international norms regarding the use of HEU in civilian applications. In response to the growing international consensus that favors LEU-based technologies, Russia has chosen not to use HEU in a number of projects that it markets internationally. In particular, its new-generation icebreakers and floating nuclear power plants are expected to use LEU-based fuel. As part of its strategy to enter the international market for medical isotopes, Russia also has been working on switching to LEU-based technologies. The success of the program to convert medical isotope production to LEU, by establishing a new international norm, suggests that a similar effort can be considered for industrial isotope production, which is currently responsible for a substantial share of HEU demand in Russia.

Although Russia has been sensitive to international norms of HEU use in its exports, it has no policy that would restrict the use of HEU in its internal projects, such as new research and space reactors or defense-related applications. Absent a strong commitment of its nuclear industry to HEU minimization, the effort to reduce the risks associated with the use of HEU can focus on conversion and HEU cleanout at those sites that have already made some progress in this area, strengthening the physical protection at those sites that continue to use HEU, and on creating conditions that would encourage operators to consider conversion or elimination of HEU.

The analysis presented in this report shows that there are a number of HEU reactors that completed most of the preparatory work for LEU conversion (see Chapter 3). These include the reactors that participated in the U.S.-Russian conversion feasibility studies, but other reactors should be considered as well. Of particular interest are the sites where reactor conversion can result in complete HEU cleanout—the IRT-MEPhI and IRT-T reactors at the Moscow Institute of Physics and Engineering and the Tomsk Polytechnic Institute respectively, the IVV-2M reactor at the Institute of Reactor Materials, and the VVR-Ts at the Obninsk branch of the Karpov Scientific Research Institute of Physical Chemistry. Indeed, conversion of the IRT-MEPhI reactor was already discussed in practical terms in the context of the U.S.-Russian joint feasibility studies project.[383] The VVR-Ts reactor was not included in this project. The reactor probably could use the LEU fuel developed for the VVR-K reactor in Kazakhstan, however.

Another site that can be targeted for a complete cleanout is the Scientific Research Institute for Instruments (NIIP) in Lytkarino. The institute operates the BARS-4 pulsed reactor and is upgrading the IRV-M2 steady-state reactor. It is possible that, with the right incentives and sufficient funding, NIIP can forego the IRV-M2 upgrade and decommission the BARS-4 facility. The incentives would have to be rather strong, however, since the closure of these facilities could affect the core mission of the institute.

The work on conversion and HEU cleanout does not have to be limited to these facilities. Meaningful HEU minimization effort at other sites would require a more systematic approach, however, and may not bring substantial benefits in the short term. Efforts at sites that continue to operate HEU facilities should, therefore, focus on strengthening physical protection and improving the material control and accounting system. Operators should also be encouraged to close down underused facilities, consolidate HEU stocks and eliminate the unnecessary transfer of HEU within the site.

Strengthening nuclear security arrangements at individual sites and industry-wide is probably one of the biggest challenges in managing the risks associated with the use of HEU. It is also the task that should be given the highest priority, since HEU will remain in active use for many years to come.

One aspect of nuclear security that deserves special attention is regulatory oversight. As described in Chapter 6, existing regulatory arrangements do not provide independent oversight of some of the defense-related activities and facilities that are regulated by Rosatom. The civilian regulatory agency, Rostekhnadzor, does not seem to have the capacity and institutional power to ensure consistent implementation of physical protection regulations at all facilities within its purview. Strong and independent regulatory oversight can be an important factor in encouraging operators to consider converting or shutting down their HEU facilities. Finding a way to strengthen Russia's national regulator is, therefore, very important.

Historically, nuclear security has not been open to international oversight. Recently, the IAEA has begun to provide advisory services, but their scope is rather limited and they may not be applicable to defense-related activities. In any case, Russia has never used these services. Development of a new nuclear security framework that would allow closer cooperation between all states on matters related to protection of fissile materials has long been on the agenda of the expert community.[384] A recent report by a high-level advisory board to the U.S. Secretary of Energy noted that "build[ing] a global nuclear materials security system of effective nuclear security norms, standards, and best practices worldwide […] will require the creation of a stronger global nuclear security architecture—an ambitious objective being pursued internationally in part through the Nuclear Security Summit process."[385] The Nuclear Security Summit process had the potential to create at least some elements of this new framework, but has largely failed to do so. Until recently, the United States provided Russia with some assistance in this area, but most of these projects ended in 2015–2016. This may present an opportunity for the two countries to start examining options for building a comprehensive international nuclear security framework that would support cooperation between civilian and defense regulatory agencies, operators of nuclear facilities, security providers, and national security and law enforcement agencies. They should also establish a framework for the exchange of best practices, the development of nuclear security culture, as well as to facilitate a discussion of common approaches to threat assessment.

Finally, the long-term success of HEU minimization will require creating conditions that would encourage operators to discontinue the use of HEU. Stronger regulatory oversight, operator cost-sharing for physical protection and a strengthened international norm against the use of HEU in civilian applications can all raise the cost of maintaining HEU operations.

At the same time, positive incentives must be provided as well. This can be done by expanding the range of opportunities available to researchers and commercial operators, so they can continue their work without HEU. International cooperation that would reduce the need for HEU critical facilities would include sharing of benchmark data, computer codes, and computational resources that are required to simulate future reactor cores.[386] Russian scientists already participate in a number of projects that involve sharing of data and expertise, such as the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and the Generation IV International Forum and IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). Since Russia is one of the few countries with active fast-neutron reactor development programs, it will likely retain a number of HEU research facilities to support this effort. However, as cooperation in this area expands further, key research using HEU could be consolidated in a smaller number of international "centers of excellence" making it possible to close down non-essential research facilities.

In summary, Russia has made significant progress in reducing its use of HEU, closing down HEU-using research facilities, and helping to remove the material from third countries. Further progress in this area will critically depend on the development of a comprehensive approach to HEU minimization that would be supported by the Russian nuclear community as well as Russian political leadership. Historically, international cooperation has proven to be a powerful and essential instrument in advancing the cause of HEU minimization. The termination of most U.S.-Russian cooperative projects in 2015 has definitely made more difficult productive work on reactor conversion and nuclear security. Regular contacts between U.S. and Russian scientists, officials of the nuclear industries and regulatory bodies will definitely continue, however, whether on a bilateral basis or in multilateral international settings. This will open the way for discussions of a strategic approach to reducing the use of HEU and prepare ground for future cooperative projects. It is important to keep this issue on the agenda and to continue work on all aspects of HEU minimization.

A APPENDIX
HEU-fueled reactors and research facilities in Russia

This appendix provides information about facilities in Russia that use HEU (or plutonium) or used it in the past. The categories include steady state reactors (SS), critical assemblies (CA), subcritical assemblies (SCA), naval prototype reactors (NV), and pulsed reactors (PR).

Name	Other names	Description	First criticality	Status	Category
National Research Centre Kurchatov Institute, Moscow					
IR-8	IRT	Water-water, pool-type. Operated as IRT-1000/IRT-M during 1957–1979 with EK-10 10%, IRT 36%, and IRT-2M 90% fuel.[387] Since 1981 uses IRT-3M 90% HEU fuel. 8 MW.[388]	1957[389]	In operation[390]	SS
OR		Water-water, tank type. Power up to 300 kW. S-36 36% HEU fuel.[391]	1954[392]	In operation[393]	SS
Gamma		Water-water, tank-type. Prototype of an Arctic power station. 125 kW.[394] 36% HEU fuel.[395]	1982	Being decommissioned. All fuel removed as of 2015.[396]	SS
RFT	RPT	Water-graphite, channel type. 10 MW and 10% LEU fuel, 20 MW and 90% HEU fuel after reconstruction in 1957.[397]	1952	Shut down in 1962. Spent fuel was placed in storage.[398]	SS
MR		Water-beryllium, channel type, 20 MW, 40 MW after reconstruction in 1986. 90% HEU MR-type fuel.[399]	1963	Shut down in 1993. Spent fuel was placed in storage.[400]	SS
VVR-2		Water-water, tank type. 300 kW. 2% and 10% LEU fuel, 36% HEU VVR-type fuel.[401]	1954	Shut down in 1983.[402] Spent fuel placed in storage.[403]	SS
Argus		Aqueous solution of UO_2SO_4. 1.71 kg of 90% HEU in 22 liters of solution. 20 kW.[404]	1981[405]	Converted to LEU in July 2014.[406] In operation.[407]	SS
Gidra	Hydra, IIN-3M	Aqueous solution of UO_2SO_4. 3.2 kg of 90% HEU in 40 liters of solution. Average power 10 kW.[408]	1972[409]	In operation[410]	PR
Aksamit		Space-reactor research. Includes RP-50 critical assembly.[411] Uranium-nitride 90% HEU fuel.[412]	1986[413]	In operation[414]	CA
RP-50		Space-reactor research. Reactor-converter. Part of the Aksamit facility.[415]	1986[416]	Does not operate independently from Aksamit[417]	CA
Narciss-M2	Narciss, Nartsiss-M2	Neutronic model of Yenisey reactor-converter (thermionic). UO_2-based 96% HEU fuel. In 1970–1983 operated as Narciss.[418]	1970[419]	In operation[420]	CA

Iskra		Space-reactor research. Included Chaika and Filin critical assemblies.[421] U-Al alloy and uranium nitride 90% HEU fuel.[422]	1996[423]	Shut down in 2008[424]	CA
Filin		Space-reactor research. Was part of the Iskra facility.[425] Transferred to the Grog facility. 100 W. Uranium carbide-based 90% HEU fuel.[426]	1996[427]	Does not operate independently[428]	CA
Chaika	Chayka	Space-reactor research. Was part of the Iskra facility.[429] Transferred to the Grog facility. 100 W. Uranium nitride-based 90% HEU fuel.[430]	1996[431]	Does not operate independently[432]	CA
Astra		High-temperature gas-cooled reactor research. Pebble-type UO_2-graphite 21% HEU fuel.[433]	1981[434]	Operation suspended for modernization[435]	CA
Romashka		Reactor-converter (thermoelectric). 30 kW. UC_2 fuel with 90% HEU.[436]	1964	Shut down in 1966. 44.5 kg of spent fuel was placed in storage.[437]	SS
Topaz-2		Reactor-converter (thermionic). 100 kW. UO_2-based 90% HEU fuel.[438]	1973	Shut down in 1986. 112.3 kg of spent fuel was placed in storage.[439]	SS
SF-1		Propulsion reactor research. 100 W. 21–90% HEU fuel.[440]	1972[441]	Operated in 2013.[442] Being decommissioned.[443]	CA
SF-3		Propulsion reactor research. 100 W. UZr-alloy 90% HEU fuel, 21% UO_2-based fuel.[444]	1979[445]	Mothballed before 2003.[446] Decommissioned. Material removed.[447]	CA
SF-5		Propulsion reactor research. 100 W. Uranium hydride-zirconium fuel with 24% and 36% HEU.[448]	1990[449]	Mothballed before 2003.[450] Decommissioned. Material removed.[451]	CA
SF-7		Propulsion reactor research. 100 W. Uranium-zirconium alloy-based 80% HEU fuel.[452]	1975[453]	Operated in 2013.[454] Being decommissioned.[455]	CA
Delta		Propulsion reactor research. 100 W. UO_2-based 80% and 90% HEU fuel.[456]	1985[457]	In operation[458]	CA
Kvant		Propulsion reactor research. 1 kW.[459] 90% HEU fuel.[460]	1990[461]	In operation[462]	CA
Efir-2M	Ephir-2M	Physical model of the Ruslan reactor.[463] 100 W. UO_2-based 90% HEU fuel.[464]	1973[465]	In operation[466]	CA
FM MR	MR CA	Physical model of the MR reactor. 100 W. 90% HEU fuel.[467]	1971[468]	Shut down. Decommissioned in 2004.[469]	CA
Mayak		Uranium-aluminum alloy fuel.[470] Pulsed reactor to model VVR-2 active zone. EK-10 10% LEU and S-36 36% HEU fuel.[471]	1967[472]	Shut down between 1985 and 2000.[473]	PR

UG		Modeling cores of uranium graphite production reactors.[474] May have used 90% HEU fuel in some channels.	1965[475]	Mothballed.[476] Being decommissioned.	CA
Institute of Theoretical and Experimental Physics (ITEF), Moscow					
TVR		Heavy-water reactor. 2.5 MW. UO_2-aluminum 90% HEU fuel.[477] 90% HEU since 1963.[478]	1949[479]	Shut down in 1986[480]	SS
MAKET		Physical model of the [LF-2 Lyudmila] heavy-water production reactor. 1 kW.[481] Up to 90% HEU fuel.[482]	1976[483]	In operation[484]	CA
ELYANG		Target blanket for an accelerator-driven system. 90% HEU fuel of the TVR reactor.[485]	—	Project terminated in 2011[486]	SCA
Moscow Institute of Physics and Engineering (MEPhI), Moscow					
IRT-MEPhI	IRT, IRT-2500	Water-water, pool type. 2.5 MW.[487] IRT-2M and IRT-3M 90% HEU fuel.[488]	1967	Suspended for reconstruction	SS
Scientific Research Institute for Instruments (NIIP), Lytkarino					
IRV-M2		Water-water, pool-type. 4 MW. In 1974–1991 operated as IRV-M1 at 2 MW.[489] IRT-2M 90% or 36% HEU fuel.[490]	1974	Shut down for reconstruction in 1991.[491] Unlikely to be completed.[492] Some HEU fuel on site.	SS
BARS-2		Pulsed reactor with U-Mo alloy. 90% HEU. Operated at VNIITF until 1970.[493]	1969[494]	Shut down in 2000.[495] All material removed before 2008.[496]	PR
BARS-3M		Pulsed reactor with U-Mo alloy. 90% HEU.[497] Operated as BARS-3 at VNIITF in 1972–1988.[498]	1972[499]	Shut down in 1997.[500] All material had been removed by 2008.[501]	PR
BARS-4		U-Mo alloy. 90% HEU. In 1979–1980 operated at VNIITF.	1979[502]	In operation[503]	PR
TIBR-1M	TIBR	Transportable pulsed reactor. U-Mo alloy. 90% HEU.[504] In 1970–1975 operated at VNIIEF as TIBR.[505]	1970[506]	Shut down in 2001.[507] All material had been removed before 2008.[508]	PR
IIN-3M		Aqueous solution of UO_2SO_4. 90% HEU.[509]	1972[510]	Shut down in 2005. Material removed by 2010.[511]	PR
VVRL-02	VRL-02	Transportable pressure-vessel water-water reactor brought for decommissioning from the Semipalatinsk site. 100 kW.[512] Likely HEU fuel.[513]	1974[514]	Decommissioned between 2003 and 2011.[515] All material has been removed.[516]	SS
VVRL-03	VRL-03	Transportable pressure-vessel water-water reactor brought for decommissioning from the Semipalatinsk site. 100 kW.[517] Likely HEU fuel.[518]	1961[519]	Shut down in 1969.[520] Decommissioned between 2003 and 2011.[521] All material has been removed.[522]	SS
Stend T		Space-reactor research. Tests of the BES-5 Buk-type reactors No. 16, No. 25, No. 32, No. 57 and the Yenisey-type reactor transferred from Krasnaya Zvezda.[523]	1963	Decommissioned. All material has been removed.[524]	SS

Scientific Research and Design Institute of Power Engineering (NIKIET), Moscow					
RUGK		High-temperature gas-cooled reactor for a space-propulsion system. Most likely HEU.	—	Under development[525]	SS
Skif		Physical models of reactor zones, including that of RUGK.[526]	—	Under development	CA
FS-2		Subcritical assembly. 36% HEU fuel.[527]	1972[528]	Shut down for reconstruction in 1998.[529] Restarted in October 2015.[530]	SCA
Petersburg Nuclear Physics Institute, Gatchina					
VVR-M	WWR-M	Water-water, pool-type reactor. 18 MW.[531] In 1959–1963 used VVR-M1 20% HEU, in 1963–1979 used VVR-M2 36% HEU, and since 1978 has used VVR-M5 90% HEU fuel.[532]	1959[533]	In operation[534]	SS
FM VVR-M		Physical model of the VVR-M reactor. VVR-M HEU fuel.[535]	1959	Shut down	CA
PIK		High-flux research reactor. 100 MW. UO_2 in Cu-Be matrix 90% HEU fuel.[536]	2011[537]	In operation at 100 W[538]	SS
FM PIK	PIK PM	Physical model of the PIK reactor. 100 W. PIK 90% HEU fuel.[539]	1983[540]	In operation[541]	CA
Research Institute of Atomic Reactors (NIIAR), Dimitrovgrad					
SM-3		High-flux research reactor. Pressure vessel. 100 MW. In 1961–1991 operated as SM-2. UO_2 in Cu-Be matrix 90% HEU fuel.[542]	1961[543]	In operation	SS
MIR.M1	MIR-M1	Material test reactor. Water-cooled, Be-moderated. 100 MW. UO_2-based MR 90% HEU fuel.[544]	1966[545]	In operation	SS
RBT-6		Water-water pool reactor. 6 MW. SM-3 spent fuel and fresh SM-3 90% HEU fuel.[546]	1975[547]	In operation	SS
RBT-10/1		Water-water pool reactor 10 MW. SM-3 spent fuel and fresh SM-3 90% HEU fuel.[548]	1982[549]	Shut down in 2004.[550] Decommissioned.	SS
RBT-10/2		Water-water pool reactor. 10 MW. SM-3 spent fuel and fresh SM-3 90% HEU fuel.[551]	1982[552]	In operation	SS
AST-1	Arbus	Prototype power reactor. Organic coolant and moderator. Operated as Arbus in 1963–1978 at 5 MW (750 MWe). 36% HEU fuel.[553] Since 1979 12 MW.[554] AST 90% HEU fuel.[555]	1963[556]	Shut down in 1988[557]	SS
BOR-60		Sodium-cooled prototype of power fast reactor. 60 MW.[558] Pu and UO_2-based 45–90% HEU fuel.[559]	1968	In operation[560]	SS
FM SM-3	SM	Physical model of the SM-3 reactor. 100 W. SM-3 90% HEU fuel.[561]	1970[562]	In operation[563]	CA
FM MIR.M1	CA MIR.M1, MIR	Physical model of the MIR.M1 reactor. MR 90% HEU fuel.[564]	1966[565]	In operation[566]	CA

Tomsk Polytechnic Institute, Tomsk					
IRT-T		Water-water, pool type. 6 MW.[567] Until 1971 EK-10 10% LEU fuel. In 1971–1979 used IRT-2M fuel. Currently IRT-3M 90% HEU fuel.[568]	1967[569]	In operation	SS
Institute of Reactor Materials (IRM), Zarechnyy					
IVV-2M		IRT-type, water-cooled, pool-type. In 1966–1977 operated as IVV-2 at 10 MW with IVV-2 90% HEU fuel. Since 1977 has used IVV-2M 90% HEU fuel. 15 MW.[570]	1966[571]	In operation	SS
Beloyarsk Nuclear Power Plant, Zarechnyy					
BN-600		Sodium-cooled fast neutron power reactor. 17% LEU and 21% and 26% HEU fuel.[572]	1980	In operation	SS
BN-800		Sodium-cooled fast neutron power reactor. HEU and Pu fuel.[573]	2014[574]	In operation	SS
Institute of Physics and Power Engineering (FEI), Obninsk					
BR-1		Fast neutron reactor. 100 W. Pu fuel.[575]	1955[576]	Decommissioned in 2011	CA
BR-2		Mercury-cooled fast reactor. 100 kW. Pu fuel.[577]	1956[578]	Shut down in 1958[579]	SS
BR-3		Fast-thermal system. BR-1 reactor zone with a different blanket. Pu fuel.[580]	1957	Decommissioned	SCA
BR-10	BR-5	Sodium-cooled fast reactor. In 1958–1973 operated as BR-5 at 5MW. 10 MW. 80% and 90% HEU fuel.[581]	1958[582]	Shut down in 2002.[583] Being decommissioned.[584]	SS
BFS-1		Fast-neutron facility. 200 W. Pu and up to 90% HEU fuel elements.[585]	1962[586]	In operation[587]	CA
BFS-2		Fast-neutron facility. 1 kW. Pu and up to 90% HEU fuel elements.[588]	1969[589]	In operation[590]	CA
TES-3		Transported light-water power reactor. 8.8 MW (1.5 MWe). 2.4–3.6% LEU and 80% and 90% HEU fuel.[591]	1961[592]	Shut down in 1978[593]	SS
Stend T-2	Stand T-2	Space reactor research facility. Tests of Topaz reactors. 21% to 90% HEU fuel.[594]	1970[595]	Shut down in 1998[596]	CA
RF-GS		Aqueous solution of uranyl nitrate. 90% HEU.[597]	1962[598]	Shut down in 2003[599]	CA
SGO		Criticality experiments. 100 W. UO_2, U-Be 90% HEU fuel.[600]	1968[601]	Shut down in 1994[602]	CA
Strela		Space reactor research facility. Tests of Topaz reactors. 100 W. 90% HEU fuel.[603]	1968[604]	Shut down. Decommissioned in 2010.[605]	CA
KOBR	KBR, KOBRA, COBRA, COBR	Ring fast critical assembly. Up to 90% HEU fuel.[606] 300 W.[607]	1970[608]	Shut down. Decommissioned in 2002.[609]	CA
FS-1M		Space reactor research facility. 100 W. 90% HEU fuel.[610]	1970[611]	In operation[612]	CA
K-1		Critical facility.[613] HEU fuel.	1989[614]	Being refurbished[615]	CA

UKS-1M	UCF-1M	Nuclear lasers research. 90% HEU.[616]	1989[617]	Not operational	SCA
BARS-6		Two-core pulsed reactor. 10 kW in static mode. U-Mo metal fuel with 90% HEU.[618] Part of the Stend B facility.	1994[619]	In operation.[620] Is being prepared for shutdown and decommissioning.	PR
OKUYaN		Nuclear lasers research. Contains more than 90% HEU.[621] Operates with BARS-6 as part of the Stend B facility.[622]	1999[623]	In operation.[624] Will be shut down with BARS-6.	SCA
PF-4	PF	Modeling of cores of fast-neutron reactors. Pu and 90% HEU fuel elements.[625]	1971[626]	Decommissioned before 2010[627]	CA
FG-5		Criticality experiments. No information on fuel.	1967[628]	Was under reconstruction in 2006.[629] Decommissioned in 2009.[630]	CA
PS-2		No information on fuel.[631]		Decommissioned in 2006 [632]	CA
Various CA		FEI operated more than 20 critical assemblies. Some of them are PNFT, F, GROT-2, V-1M.[633] No further information about these facilities is available.			CA
27/VT		Prototype naval reactor, lead-bismuth coolant, U-Be alloy in Be matrix HEU fuel. 70 MW.[634]	1958[635]	Shut down in 1976. Fuel removed to storage.[636] Being decommissioned.[637]	NV
27/VM		Prototype pressurized-water naval reactor. 70 MW. LEU and HEU fuel.[638]	1956	Shut down in 1986. Fuel removed to storage.[639] Being decommissioned.[640]	NV
Obninsk Branch of the Karpov Scientific Research Institute of Physical Chemistry (NIFKhI), Obninsk					
VVR-Ts	WWR-TS, VVR-C	Water-water, tank-type reactor. 15 MW. VVR-Ts 36% HEU fuel.[641]	1964[642]	In operation[643]	SS
Joint Institute for Nuclear Research, Dubna					
IBR		Periodic pulsed fast-neutron reactor.[644] Most likely used HEU and Pu.	1960[645]	Shut down in 1968[646]	PR
IBR-30		Periodic pulsed reactor or booster. HEU and Pu fuel.[647]	1969[648]	Shut down in 2001[649]	PR
IBR-2M	IBR-2	Periodic pulsed reactor. Operated as IBR-2 in 1984–2006. Pu fuel.[650]	1984[651]	In operation[652]	PR
IREN		Subcritical assembly. Pu fuel.[653]		Under construction. No material on site.[654]	SCA
Central Physical-Technical Institute of the Ministry of Defense (TsFTI MO), Sergiyev Posad					
BARS-1	BARS	Pulsed reactor. U-Mo alloy, 90% HEU.[655] Transferred from VNIITF in 1966.[656]	1964[657]	Dismantled before 2002[658]	PR
Priz		Static fast-neutron reactor.[659] Irradiation of military equipment. 1 kW. Metal 90% HEU fuel.[660]	1970[661]	Status unknown	PR

Scientific Research Technological Institute (NITI), Sosnovy Bor					
VAU-6s		Prototype pressurized-water, naval auxiliary power unit.[662] Likely 21–36% HEU fuel.	1971[663]	Shut down before 2004. Being decommissioned.[664]	NV
KM-1		Prototype naval reactor (Project 705 Alfa). Lead-bismuth coolant.[665] 90% HEU fuel.	1978[666]	Shut down in 1986.[667] Fuel is being removed.[668]	NV
KV-1		Prototype pressurized-water, naval reactor (OK-650).[669] 21–45% HEU fuel.	1975[670]	In operation[671]	NV
KV-2		Prototype pressurized water naval reactor.[672] Likely HEU fuel.	1996[673]	Shut down in 2014. Fuel removed in 2017.[674]	NV
AMB-8		Prototype naval reactor. Liquid-metal coolant.[675]	—	Under construction[676]	NV
Machine-Building Plant (MSZ), Electrostal					
Stend-2		Tests of active zones of nuclear reactors (probably second-generation naval reactors).[677] 2 kW.[678]	1967[679]	Decommissioned[680]	CA
Stend-3		Tests of active zones of transport reactors (probably second-generation naval reactors).[681] 2 kW.[682]	1967[683]	Decommissioned in 2012.[684]	CA
All-Russian Research Institute of Chemical Technology (VNIIKhT), Moscow					
SO-2M		Subcritical assembly. Neutron measurement research. 36% HEU in polyethylene matrix.[685]	1975[686]	Decommissioned in 2011.[687]	SCA
Krylov Central Research Institute, St-Petersburg					
G-1		Naval reactor research. 200 W. Enrichment unknown.	1989[688]	Shut down in 1998.[689] Decommissioned in 2002.[690] All HEU removed by 2007.[691]	CA
MER		Naval reactor research. Enrichment unknown.	1964[692]	Shut down in 1969.[693] Decommissioned in 2002.[694] All HEU removed by 2007.[695]	CA
R-1		Naval reactor research. Enrichment unknown.	1991[696]	Shut down in 1999.[697] Decommissioned in 2002.[698] All HEU removed by 2007.[699]	SCA
Experimental Design Bureau of Machine-Building (OKBM), Nizhniy Novgorod					
ST-659		Neutronic models of light-water naval reactors. Up to 100 W. Variable U-235 content.[700] Some HEU fuel.	1963[701]	In operation[702]	CA
ST-659L		Naval reactors-related research. Likely HEU.	1979[703]	Decommissioned in 2002.[704]	CA
ST-1125		Neutronic models of light-water naval reactors. Up to 300 W. Variable U-235 content.[705] Some HEU fuel.	1975[706]	In operation[707]	CA
ST-1120		Naval reactors-related research. Likely HEU.	1975	Shut down in 1996.[708]	CA

Mayak Production Association, Ozersk					
Ruslan		Light-water tritium production reactor. 1000 MW. 90% HEU fuel.[709]	1979[710]	Under modernization since 2011. Expected to resume operations in 2018.[711]	SS
LF-2	Lyudmila	Heavy-water tritium production reactor. 1000 MW. 90% HEU fuel.[712]	1987[713]	In operation	SS
OK-180		Heavy-water tritium production reactor. 80% HEU fuel elements since 1960.[714]	1951[715]	Shut down in 1966.[716]	SS
OK-190		Heavy-water tritium production reactor. 80% HEU fuel elements since 1960.[717]	1955[718]	Shut down in 1965.[719]	SS
OK-190M		Heavy-water tritium production reactor. 80% HEU fuel elements.[720]	1966[721]	Shut down in 1986.[722]	SS
AI	AI-IR	Tritium production graphite reactor. 80% HEU fuel in 1966–1967, 90% HEU since 1967.[723]	1951[724]	Shut down in 1987.[725]	SS
A		Plutonium production reactor. Used “spike” HEU fuel elements since 1966–1967.	1948[726]	Shut down in 1987.[727]	SS
AV-1	OK-110-1	Plutonium production reactor. Used “spike” HEU fuel elements since 1966–1967.	1950[728]	Shut down in 1989.[729]	SS
AV-2	OK-110-2	Plutonium production reactor. Used “spike” HEU fuel elements 1966–1967.	1951[730]	Shut down in 1990.[731]	SS
AV-3	OK-110-3	Plutonium production reactor. Used 21% HEU fuel since 1961.[732] Used “spike” 90% HEU fuel elements.	1952[733]	Shut down in 1990.[734]	SS
UF_6 reactor		UF_6-cooled research reactor. 90% HEU. 1.5 kw.[735]	1957[736]	Decommissioned	SS
Siberian Chemical Combine, Seversk					
I-1		Plutonium production reactor. Used “spike” 90% HEU fuel elements.	1955[737]	Shut down in 1990.[738]	SS
EI-1		Plutonium production reactor. Used “spike” 90% HEU fuel elements.	1958[739]	Shut down in 1990.[740]	SS
ADE-3	OK-140[741]	Plutonium production reactor. Used “spike” 90% HEU fuel elements.[742]	1961[743]	Shut down in 1990.[744]	SS
ADE-4	OK-204	Plutonium production reactor. Used “spike” 90% HEU fuel elements.[745]	1964[746]	Shut down in 2008.[747]	SS
ADE-5	OK-205	Plutonium production reactor. Used “spike” 90% HEU fuel elements.[748]	1965[749]	Shut down in 2008.[750]	SS
Mining and Chemical Combine, Zheleznogorsk					
AD	OK-120	Plutonium production reactor. Used “spike” 90% HEU fuel elements.	1958[751]	Shut down in 1992.[752]	SS
ADE-1	OK-135	Plutonium production reactor. Used “spike” 90% HEU fuel elements.[753]	1961[754]	Shut down in 1992.[755]	SS
ADE-2	OK-206	Plutonium production reactor. Used “spike” 90% HEU fuel elements.[756]	1964[757]	Shut down in 2010.[758]	SS

All-Russian Scientific Research Institute of Experimental Physics (VNIIEF), Sarov					
BIGR		Irradiation experiments. Ceramic UO_2-graphite fuel. 90% HEU.[759]	1977[760]	In operation	PR
LM-4		Nuclear pumped laser research. A laser module that uses BIGR as a neutron source. Gram quantities of U-235.[761]	1994[762]	Status unknown	SCA
LM-8		A laser module that uses BIGR as a neutron source.[763] May have replaced LM-4. Likely gram quantities of U-235.	—	Operational[764]	SCA
UFN-P		Irradiation experiments. Will work with BIGR. 90% HEU.[765]	—	Under development	SCA
BR-1M	BR-1	U-Mo alloy. 90% HEU. During 1979–1986 and after 1990 operated as BR-1. Started as BR-1M in 2009.[766]	1979[767]	In operation	PR
BR-K1		U-Mo alloy. 36% HEU.[768]	1995[769]	In operation	PR
BIR-2M	BIR, BIR-1, BIR-2	U-Mo alloy. 85% HEU.[770] In 1965–1970 operated as BIR, in 1970–1986—as BIR-2.[771]	1965[772]	Status unknown. Most likely dismantled.	PR
PKS	BIR+PKS	Metal 90% HEU. Worked with BIR as part of two-zone reactor.[773]	1974[774]	Status unknown. Most likely dismantled.	SCA
GIR-2	GIR, GIR-1	U-Mo alloy. 36% and 90% HEU. In 1984–1988 operated as GIR-1. Since 1993 has operated as GIR-2.[775]	1984[776]	In operation	PR
FKBN-2M		Study of critical systems. U and U-Mo alloy with 36% HEU, 75% HEU, 90% HEU, U-233, and Pu elements. Operated as FKBN, FKBN-1, FKBN-2.[777] As FKBN-2M since 1976.[778]	1949[779]	Under modernization[780]	CA
MSKS		Study of critical systems with external neutron source. Used FKBN fuel element set.[781]	1955[782]	Status unknown	CA
VIR-2M		Aqueous solution of uranyl sulfate. 90% HEU.[783] Previously operated as VIR-1, VIR-1M, VIR-2.[784]	1965[785]	In operation	PR
LUNA-2M		Nuclear pumped laser research. Uses VIR-2M as a neutron source. Gram quantities of U-235.[786]	1975[787]	Status unknown	SCA
LUNA-2P		Nuclear pumped laser research. Uses VIR-2M as a neutron source. Gram quantities of U-235.[788]	1987[789]	Status unknown	SCA
IKAR-S		Study of the reactor core of an IKAR-500 pulsed reactor. U-Al dispersion fuel, 90% HEU.[790]	2008[791]	In operation[792]	CA
All-Russian Scientific Research Institute of Technical Physics (VNIITF), Snezhinsk					
IGRIK		Aqueous solution of uranyl sulfate. 90% HEU.[793]	1976[794]	In operation[795]	PR
YAGUAR		Aqueous solution of uranyl sulfate. 90% HEU.[796]	1990[797]	In operation[798]	PR
ELIR		Aqueous solution of uranyl sulfate (originally uranyl nitrate). 90% HEU.[799]	1966[800]	Dismantled in 1984.[801]	PR

EBR-200		Irradiation experiments. Worked as part of the FKBN-I facility as well as separately. U-Mo alloy, 90% HEU fuel.[802]	1967[803]	Shut down in 1973.[804]	PR
EBR-L	EBR-200M, FBR-L	Irradiation and nuclear lasers research. U-Mo alloy 90% HEU fuel. Successor to EBR-200. Operates as EBR-L since 1981.[805]	1976[806]	In operation[807]	PR
FKBN-I		Irradiation research. Metal 90% HEU.[808] After 1967 worked with EBR-107, EBR-110, EBR-120, and EBR-135 active zones.[809]	1964[810]	Status unknown	PR
EBR-107		Irradiation experiments. Worked as part of the FKBN-I facility as well as separately. Copper reflector. Uranium metal 90% HEU fuel.[811]	1967[812]	Dismantled before 1973[813]	PR
EBR-120		Irradiation of military equipment. Briefly worked as part of the FKBN-I facility. Uranium metal 90% HEU fuel.[814]	1967[815]	Status unknown. Most likely dismantled.[816]	PR
EBR-135		Irradiation of military equipment. Briefly worked as part of the FKBN-I facility. Uranium metal 90% HEU fuel.[817] Did not work as a pulsed reactor.[818]	1967[819]	Status unknown. Likely dismantled.[820]	PR
EBR-110		Irradiation experiments. Worked as part of the FKBN facilities. U-Mo alloy. 90% HEU.[821]	1967[822]	Dismantled before 1973[823]	PR
RUS-V	RUS	Operated as RUS with EBR-200M as two-zone reactor in 1978–1979.[824] Irradiation of military equipment. RUS-M and RUS-P active zones. Metal 90% HEU.[825]	1977[826]	Status unknown. Was operational in 2002.[827]	PR
FKBN		Criticality research. In 1958 used U-233 fuel. 90% HEU since 1959.[828]	1958[829]	Shut down in 1969.[830]	CA
FKBN-2	FKBN-M	Criticality research. In 1971–1998 operated as FKBN-M. As FKBN-2 since 2000.[831] Includes four sets of spherical active zones and the ROMB cylindrical set. Metal 90% HEU.[832]	1971[833]	In operation[834]	CA
BARS-5		Irradiation experiments. Two-zone reactor. U-Mo alloy with 90% HEU.[835]	1985[836]	In operation[837]	PR
RUN-1		Neutron multiplier. Used BARS-5 as neutron source. Likely U-Mo alloy, 90% HEU.[838]	1990[839]	Status unknown. Likely dismantled ca. 1994.	SCA
RUN-2	RUN	Neutron multiplier. Used BARS-5 as neutron source. U-Mo alloy, 90% HEU.[840]	1994[841]	In operation[842]	SCA

B

APPENDIX

Soviet-provided research reactors and other facilities abroad

This appendix provides information about research reactors and other facilities outside of Russia that were built with Soviet assistance or used fuel supplied by the Soviet Union or Russia. The categories include steady state reactors (SS), critical assemblies (CA), subcritical assemblies (SCA), naval prototype or training reactors (NV), pulsed reactors (PR), and fast neutron reactors (FR).[843]

Name	Other names	Description	First Criticality	Status	Category
Belarus					
Joint Institute for Nuclear and Power Research Sosny, Minsk					
Yalina-B	Yalina Booster	90% and 36% HEU fuel.[844]	2005	Conversion is underway.[845] As of 2013, the fuel was removed and placed into storage.[846]	SCA
Yalina-T	Yalina Thermal	EK-10 10% LEU fuel.[847]	2000	Operational[848]	SCA
Hyacinth	Giatsint, Giacint	10% LEU to 90% HEU fuel.[849] Reconstruction in 1998–2008.[850]	1965	Operational. LEU fuel supplied in 2010. Conversion is not completed, but scheduled.	CA
Roza		Study of uranium-water systems. Enrichment unknown.	1965	Shut down and dismantled before 2005. Fuel moved to storage.[851]	CA
Kristall	Crystal	Used to support the work on Pamir reactor.[852] Likely 45% HEU Pamir fuel.	ca. 1985	Mothballed after 1994. All fuel removed, but the core is intact. As of 2013 was in long-term suspension.[853]	CA
IRT-M	IRT-1000, IRT-2000, IRT-4000	IRT-2M 90% HEU fuel since 1977.[854]	1962	Shut down in 1987. Fully decommissioned in 1997.[855]	SS
Pamir	Pamir-630D, MNPP	Mobile 630 kW power reactor.[856] 45% HEU Pamir fuel.[857] Second reactor core was built, but never operated.	1985	Shut down in 1987. All HEU (irradiated and the fresh core) removed in 2010.	SS

Yavor	Yavar	Storage of unirradiated material. Yavor-1 is under development.[858]	—	Operational	—
Iskra		Storage of irradiated material.	—	Being decommissioned after all material was transferred to Russia in 2010.[859]	—
Bulgaria					
Nuclear Scientific Experimental and Educational Center, Institute for Nuclear Research and Nuclear Energy, Sofia					
IRT-2000	IRT-Sofia	Initially EK-10 10% LEU fuel. Mixed EK-10 LEU and S-36 36% HEU fuel since 1980. IRT-2M with 36% HEU delivered in 2001, but never loaded.[860]	1961[861]	Shut down in 1989.[862] All HEU removed in 2008.[863]	SS
China					
China Institute of Atomic Energy (CIAE), Beijing					
SPR IAE	Swimming Pool Reactor, SPR	EK-10 10% LEU fuel.[864]	1964	Operational	SS
CEFR	China Experimental Fast Reactor	65 MW.[865] 64.4% HEU fuel supplied by Russia.[866]	2009	Operational	FR
HWRR	Heavy-water Research Reactor	Heavy water reactor. 15 MW.[867] TVR-S 3% LEU fuel.[868]	1958	Shut down in 2007.	SS
Czech Republic					
Research Centre Řež, Řež					
LVR-15	VVR-S, LWR-15 REZ,	Started as VVR-S with EK-10 10% LEU fuel in 1957. 80% HEU IRT-2M fuel since 1974. Mixed core 36% and 80% IRT-2M fuel since 1995. Last 80% HEU assembly used in 1998.[869] 20% LEU IRT-4M fuel since 2011.[870]	1957	Operational. All HEU fuel removed in 2013.[871] Produces Mo-99 with HEU targets.[872]	SS
TR-0		Heavy-water zero-power reactor. Natural uranium fuel.[873]	1972	Shut down in 1979	CA
LR-0		Tests of VVER LEU fuel assemblies.[874]	1982	Operational	CA

Czech Technical University, Prague					
VR-1	VR-1 Vrabec, VR-1 Sparrow	IRT-2M 36% HEU fuel since 1990. IRT-3M 36% HEU fuel since 1997.[875] Converted to IRT-4M LEU fuel in 2005.[876]	1990[877]	Operational. Converted to LEU. Fresh fuel removed in 2005.[878] All HEU removed in 2013.[879]	SS
Škoda JS, Plzen					
SR-0	SR-0D	EK-10 10% LEU fuel in 1971. IRT-2M 80% HEU fuel since 1975. IRT-2M 36% HEU fuel also used since 1988.[880]	1971	Shut down in 1994.[881] All HEU removed in 2013.[882]	CA
DPRK					
Nuclear Research Institute, Yongbyon					
IRT-DPRK		EK-10 10% LEU fuel until about 1974. Then IRT-type 36% and 80% HEU fuel.[883]	1965[884]	Status unknown. Last fuel supply was in 1991.	SS
CA	Critical assembly	Presumably a critical assembly to test IRT reactor fuel.	After 1965	Status unknown. Was under IAEA safeguards in the past[885]	CA
Egypt					
Nuclear Research Center, Inshas					
ET-RR-1	ETRR-1	10% LEU fuel.[886]	1961	Operational	SS
Estonia					
Naval Training Center, Paldiski					
VM-4		90 MWt. 21–45% HEU fuel. Training naval reactor.[887]	1968[888]	Shut down in 1989. Fuel removed in 1995.[889]	NV
VM-A		70 MWt. LEU or 21% HEU fuel. Training naval reactor.[890]	1983[891]	Shut down in 1989. Fuel removed in 1995.[892]	NV
Georgia					
Institute of Physics, Tbilisi					
IRT-M	IRT-2000	Operated as IRT-2000 in 1959–1967 with EK-10 10% LEU fuel. IRT-2M 90% HEU fuel since 1975.[893]	1959	Shut down in 1988.[894] All fuel removed in 1998.[895]	SS
PS-1	Razmnozhitel-1, Breeder-1	Neutron source for neutron activation analysis. UO_2 with 36% HEU.[896]	1970	Shut down. All fuel removed in 2015.[897]	SCA

Germany					
Rossendorf Research Center, Rossendorf					
RFR	Rossendorf Research Reactor, VVR-SM, WWR-SM	Started with EK-10 10% LEU fuel. ECH-1/VVR-M 36% HEU fuel since 1967.[898]	1957	Shut down in 1991.[899] Fresh HEU shipped to Russia in 2006. Spent HEU fuel moved off site in 2005.[900]	SS
Rossendorf Ring Core Reactor	RRR, Rossendorfer Ringzonenreaktor	Light-water reactor with graphite reflector. 20% HEU in U_3O_8.[901] Also 36% HEU fuel.[902]	1962	Shut down in 1991. Dismantled in 1998–2000.[903]	CA
Rossendorf Assembly for Critical Experiments	RAKE, Rossendorfer Anordnung für Kritische Experimente	Started with EK-10 10% LEU fuel.[904] Also 36% HEU fuel.[905]	1969	Shut down in 1991. Dismantled in 1998–2000.[906]	CA
Dresden Technical University, Dresden					
AKR	Ausbildungs-kernreaktor, AKR-1, AKR-2	20% LEU fuel.[907]	1978[908]	Operational with LEU[909]	CA
University of Applied Sciences Zittau/Görlitz, Zittau					
ZLFR training reactor	Zittauer Lehr- und Forschungsreaktor	ECH-1/VVR-M 36% HEU fuel.[910]	1978	Shut down in 2005	CA
Hungary					
Atomic Energy Research Institute, Budapest					
VVR-SZM	Budapest Research Reactor, BRR, VVR-SM, VVR-M2	EK-10 10% LEU fuel since 1959. VVR-SM 36% HEU fuel since 1967.[911]	1959	Converted to LEU in 2009.[912] All HEU removed between 2008 and 2013.[913]	SS
ZR-4		LEU critical assembly.[914]	1966[915]	Decommissioned	CA
ZR-6M	ZR-6	LEU critical assembly.	1972	Shut down in 1990	CA
Budapest University of Technology and Economics					
Training reactor		LEU reactor.[916]	1971	Operational	SS
Iraq					
Al Tuwaitha Nuclear Center					
IRT-5000		IRT-type 36% and 80% HEU fuel.[917]	1967	Shut down in 1991. Fresh HEU fuel removed in November 1991. Spent HEU fuel removed in 1993–1994.[918]	SS
Kazakhstan					
National Nuclear Center of the Republic of Kazakhstan, Kurchatov					
IGR	Pulsed IGR, PGR	Graphite-water pulsed reactor. 90% HEU fuel.[919]	1961	Operational	PR

IVG.1M	EWG-1	Until 1988 operated as IVG.1 experimental reactor for tests of nuclear rocket engine fuel elements.[920] Modified during 1988–1990 to serve as a material test reactor. 90% HEU fuel.[921]	1972	Operational. Being converted to LEU.[922]	SS
RA	IRGIT	Operated as IRGIT in 1978–1987. A prototype of a nuclear rocket engine.[923] 90% HEU fuel.[924]	1978[925]	Shut down in 1997. Fuel removed in May 1998.[926]	PR
Institute of Nuclear Physics, Alatau, Almaty					
VVR-K	WWR-K	VVR-K 36% HEU fuel.[927] 19.7% LEU since May 2016.	1967	Operational. Converted to LEU in 2016.[928]	SS
FM VVR-K		Critical assembly for the VVR-K reactor.	1967	Converted to LEU in 2012[929] Fuel removed in 2014.[930]	CA
BN-350 Reactor, Aktau					
BN-350		900 MWt fast neutron power reactor. Uranium fuel with 17%, 21%, and 26% enrichment. Experimental MOX and 33% HEU assemblies.[931]	1973	Shut down in 1999. Removal of all spent fuel to storage completed in November 2010.[932]	FR
Ulba Metallurgical Plant, Ust-Kamenogorsk					
Storage facility		About 600 kg of U-235 in 90% HEU.[933]	—	Material removed in 1994[934]	—
Latvia					
Nuclear Research Centre of the Latvian Academy of Sciences, Salaspils					
IRT-M	SRR, Salaspils Research Reactor, IRT-5000	EK-10 10% LEU fuel until 1975. IRT-2M 90% HEU fuel since 1975, IRT-3M 90% HEU fuel since 1979.[935]	1961	Shut down in 1998.[936] Fresh fuel removed in May 2005. Spent fuel removed in May 2008.[937]	SS
RKS-25		Started with EK-10 10% LEU fuel. Later—IRT 90% HEU fuel.[938]	1966	Shut down in 1991.[939] All HEU removed in 2008.[940]	CA
Libya					
Tajoura Research Center					
IRT-1		IRT-2M 80 % HEU fuel.[941]	1981	Converted to LEU in 2006. Fresh fuel removed in 2004 and 2006.[942] Spent fuel removed in 2009.[943]	SS

IRT CA		Critical assembly for the IRT-1 reactor.	1982	Converted to LEU in 2006.[944]	CA
Poland					
National Center for Nuclear Research, Otwock-Świerk					
Maria		MR-type 80% HEU fuel since 1974.[945] Converted to 36% HEU fuel in 2001–2002.[946] Converted to LEU in 2012.[947]	1974	All HEU removed in 2016.[948] Mo-99 production with HEU targets.[949]	SS
Anna		Water-graphite moderated critical assembly. 21% HEU fuel.[950]	1963	Decommissioned in 1977[951]	CA
Agata		MR-type 36% or 80% HEU fuel elements.[952]	1969[953]	Shut down in 1995[954]	CA
Maryla		Critical assembly that was used to test 36% HEU fuel assemblies of the Ewa reactor.[955] No fuel of its own.	1967	Decommissioned in 1973[956]	CA
Ewa	WWR-S	Initially with EK-10 10% LEU fuel. In the 1960s converted to VVR-SM and later to VVR-M2 36% HEU fuel.[957]	1958	Shut down in 1995.[958]All spent fuel removed in 2010.[959]	SS
Romania					
Horia Hulubei National Institute of Physics and Nuclear Engineering—IFIN HH, Bucharest					
VVR-S	WWR-C	Started operations with EK-10 10% LEU fuel. S-36 36% HEU fuel since 1984.[960]	1957[961]	Permanently shut down in 1997. Fresh HEU fuel removed in 2003. Spent fuel removed in June 2009.[962]	SS
Serbia					
Institute of Nuclear Sciences, Vinca					
R-A	RA	Heavy-water reactors. Initially operated with natural uranium and LEU fuel. 80% TVR-S fuel added in 1976. HEU only since 1981.[963]	1959	Shut down in 1984. Fresh fuel removed in 2002, spent fuel in 2009.[964]	SS
R-B	RB	Heavy-water zero-power reactor. Initially operated with natural uranium and LEU fuel. 80% HEU fuel since 1976.[965]	1958	Operational with LEU.[966] All HEU removed in 2002.[967]	CA

Ukraine					
Institute for Nuclear Research, Kiev					
VVR-M		Until 1963 operated with 20% VVR-M1 fuel.[968] Since then operated with VVR-M2 36% HEU and VVR-M5 90% HEU fuel.[969]	1960	Converted to VVR-M2 LEU fuel in 2008. Fresh fuel removed in 2010. All HEU removed in 2012.[970]	SS
National University of Nuclear Industry and Energy, Sevastopol					
IR-100	SNI IR-100	EK-10 10% LEU fuel. S-36 36% HEU fuel delivered, but not irradiated.[971]	1967	Temporarily shut down in March 2014. All HEU fuel removed in 2010.[972]	SS
IR-100	SPh IR-100	LEU critical assembly. Used fuel assemblies of the IR-100 reactor.[973]	1974	Shut down in 1995	CA
Subcritical assembly		Natural uranium fuel.[974]	1960	May be operational	SCA
Kharkiv Institute of Physics and Technology, Kharkiv					
Storage		124.3 kg of HEU in storage.[975] Of this, about 75 kg 90% HEU. Also 30–40 kg of 20%, 25%, and 36% HEU.[976]	—	All HEU removed in 2010 and 2012.[977]	—
Uzbekistan					
Institute of Nuclear Physics, Tashkent					
VVR-SM		Initially EK-10 10% LEU fuel. Since 1971 IRT-2M 36% HEU fuel. Later IRT-3M 90% HEU fuel. Converted to IRT-3M 36% HEU in 1998–1999 and to IRT-4M LEU fuel in 2008–2009.[978]	1959	Converted to LEU in 2009. Fresh fuel removed in 2004. Spent fuel shipped out in 1973–1991. Then in 2006 and 2012.[979]	SS
Foton Enterprise, Tashkent					
Foton	Photon, IIN-3M	90% HEU in aqueous solution of UO_2SO_4.[980]	1976	Shut down. All material removed to Russia in September 2015.[981]	PR
Vietnam					
Nuclear Research Institute, Dalat					
DNRR	IVV-9	Reconstructed from TRIGA Mark II reactor. 36% VVR-M2 fuel since 1983.[982]	1983[983]	Converted to LEU in 2007–2011.[984] All HEU fuel removed in 2007 and 2013.[985]	SS

C

APPENDIX

Shipments of Russian-origin HEU fuel to Russia

This appendix describes shipments of fresh and spent HEU fuel to Russia since 1991. Unless otherwise indicated, dates and amounts of HEU in shipments are based on IAEA data.[986] The information about the type of fuel is from Appendix B. The amounts of material are estimates.

Date	Origin	Destination	Fresh or spent fuel	Notes	Amount of material
November 15–17, 1991	Iraq, Al Tuwaitha	Russia	F	IRT-5000 reactor. 68 IRT-2M 80% HEU fuel assemblies and 10 IRT-2M 36% HEU fuel assemblies.[987]	11 kg of U-235 in 13.7 kg of 80% HEU and 1.27 kg of U-235 in 3.5 kg of 36% HEU
December 4, 1993 and February 12, 1994[988]	Iraq, Al Tuwaitha	Russia	S	IRT-5000 reactor. Two shipments. The total amount is 35 kg of HEU.[989]	35 kg of 80% and 36% HEU, irradiated
November 20, 1994	Kazakhstan, Ust-Kamenogorsk	United States, Y-12 Complex	F	581 kg of 90% HEU in various forms.[990]	About 520 kg of U-235 in 581 kg of 90% HEU
1995	Estonia, Paldiski	Russia	F+S	Fresh and spent fuel from the VM-4 and VM-A naval training reactors[991w]	About 650 kg of 20% HEU, irradiated.[992] Unknown amount of fresh fuel.
1997	Kazakhstan, Kurchatov	Russia	F	Fresh fuel from the IVG.1M reactor. 90% HEU. Dates of shipments unknown.[993]	About 14 kg of U-235 in 16 kg of 90% HEU
July 1997	Kazakhstan, Kurchatov	Russia	S	One of several shipments of spent fuel from the IVG.1M reactor. Dates of other shipments unknown. 90% HEU.[994]	About 18 kg of U-235 in 20 kg of 90% HEU
April 24, 1998	Georgia, Tbilisi	UK, Dounreay	F+S	Operation Auburn Endeavor. 3.4 kg 90% HEU in fresh and 0.64 kg of HEU in spent fuel.[995]	3 kg of U-235 in 3.4 kg of 90% HEU and 0.64 kg of 90% HEU, irradiated
May 1998	Kazakhstan, Kurchatov	Russia	S	Irradiated fuel from the RA reactor. About 8 kg of U-235 in 90% HEU.[996]	About 8 kg of U-235 in 9 kg of 90% HEU
August 8, 2002	Serbia, Vinca	Russia, NIIAR	F	5,046 TVR-S 80% HEU fuel assemblies.[997]	38.9 kg of U-235 in 48.4 kg of 80% HEU

September 30, 2003	Romania, Pitesti	Russia	F	50 IRT-2M 80% HEU fuel assemblies and 150 S-36B 36% HEU fuel assemblies.[998] Fuel for the VVR-S reactor stored in Pitesti.[999]	8.3 kg of U-235 in 10.4 kg of 80% HEU + 1.4 kg of U-235 in 3.8 kg of 36% HEU
December 23, 2003	Bulgaria, Sofia	Russia, NIIAR	F	28 IRT-2M 36% HEU fuel assemblies.[1000]	6.1 kg of U-235 in 16.9 kg of 36% HEU
March 7, 2004	Libya, Tajura	Russia, NIIAR	F	88 IRT-2M 80% HEU fuel assemblies.[1001]	13.2 kg of U-235 in 16.4 kg of 80% HEU
September 9, 2004	Uzbekistan, Tashkent	Russia, NIIAR	F	S-90 90% HEU fuel assemblies and elements, S-36 36% HEU fuel assemblies and elements, EK-10 10% LEU fuel assemblies and elements. Total 1.8 kg of U-235 in 10.2 kg of uranium.[1002]	About 1.1 kg of U-235 in 3 kg of HEU (mostly 36%)
December 21, 2004	Czech Republic, Rez	NIIAR	F	Fuel of the LVR-15 reactor and bulk UO_2. IRT-2M 36% HEU and 80% HEU fuel assemblies. Also 87.7% HEU in UO.[1003]	1.3 kg of U-235 in 3.6 kg of 36% HEU, 0.15 kg of U-235 in 0.2 kg of 80% HEU, 1.9 kg of U-235 in 2.2 kg of 90% HEU
May 25, 2005	Latvia, Salaspils	Russia	F	Fuel of the IRT-M reactor and RKS-25 critical assembly. IRT-3M 90% HEU fuel.	About 2.7 kg of U-235 in 3 kg of 90% HEU
September 27, 2005	Czech Republic, Prague	Russia	F	Fuel of the VR-1 Vrabec reactor. IRT-2M 36% HEU and IRT-3M 36% HEU fuel.[1004]	About 5 kg of U-235 in 14 kg of 36% HEU
January 10, 2006, February 14, 2006, March 20, 2006, April 15, 2006	Uzbekistan, Tashkent	Russia	S	Fuel of the VVR-SM reactor. Four shipments—10 kg, 13 kg, 14 kg, and 26 kg of HEU.[1005] Total in four shipments: 210 IRT-3M 90% HEU fuel assemblies and 42 IRT-3M 36% HEU fuel assemblies.[1006]	About 28 kg of 36% HEU and 35 kg of 90% HEU, irradiated
June 27, 2006	Libya, Tajura	Russia	F	Fuel of the IRT-1 reactor. IRT-2M 80% HEU fuel.[1007]	2.4 kg of U-235 in 3 kg of 80% HEU
August 10, 2006	Poland, Otwock-Świerk	Russia	F	Fuel of the Maria reactor. MR 80% HEU fuel.	32 kg of 80% U-235 in 39.8 kg of HEU
October 15, 2006	Czech Republic, Rez	Russia	F	Fuel assembly of the LVR-15 reactor. Likely 80% HEU.	0.16 kg of U-235 in 0.2 kg of 80% HEU
December 18, 2006	Germany, Rossendorf	Russia	F	Fuel of the Rossendorf RRR reactor. 36% HEU fuel.	96 kg of U-235 in 268 kg of 36% HEU
August 28, 2007	Poland, Otwock-Świerk	Russia	F	Fuel of the Maria reactor. MR 80% HEU fuel.	7 kg of U-235 in 8.8 kg of 80% HEU

September17, 2007	Vietnam, Dalat	Russia	F	Spare fuel of the DNRR research reactor. 36 VVR-M2 36% HEU fuel.[1008]	1.4 kg U-235 in 4 kg of HEU
November 29, 2007	Czech Republic, Rez	Russia	S	Fuel of the LVR-15 reactor. Likely 36% and 80% HEU.	80 kg of 36% and 80% HEU, irradiated
May 12, 2008	Latvia, Salaspils	Russia	S	Fuel of the IRT-M reactor. IRT-3M 90% HEU fuel.	14.4 kg of 90% HEU, irradiated
July 4, 2008	Bulgaria, Sofia	Russia	S	Fuel of the IRT-2000 reactor. S-36 36% HEU fuel.[1009]	6.3 kg of 36% HEU, irradiated
October 10, 2008	Hungary, Budapest	Russia	S	Fuel of the VVR-SZM reactor. VVR-SM 36% HEU fuel.	130.36 kg of 36% HEU, irradiated[1010]
December 25, 2008, March 1, 2009, Aptril 1, 2009, May 1, 2009	Kazakhstan, Alatau	Russia	S	Fuel of the VVR-K reactor. Four shipments—17.3 kg, 16.6 kg, 18.8 kg, and 21 kg.	73.7 kg of 36% HEU, irradiated
June 28, 2009	Romania, Pitesti	Russia	F	Fuel pellets reserved for TRIGA reactor fuel. About 20% enrichment.	About 6 kg of U-235 in 30 kg 20% HEU
June 29, 2009	Romania, Bucharest	Russia	S	Fuel of the VVR-S reactor. S-36 36% HEU fuel.	23.7 kg of 36% HEU, irradiated
July 6, 2009	Hungary, Budapest	Russia	F	Fuel of the VVR-SZM reactor. S-36 36% HEU fuel.	6.7 kg of U-235 in 18.6 kg of 36% HEU
September 13, 2009	Poland, Otwock-Świerk	Russia	S	Fuel of the Ewa reactor. VVR-M2 36% HEU fuel.	187 kg of 36% HEU, irradiated
December 21, 2009	Libya, Tajoura	Russia	S	Fuel of the IRT-1 reactor. IRT-2M 80% HEU fuel.	5.2 kg of 80% HEU, irradiated
March 18, 2010	Poland, Otwock-Świerk	Russia	S	Fuel of the Ewa and Maria reactors. VVR-M2 36% HEU and MR 36% and 80% HEU fuel.[1011]	137.4 kg of 36% and 80% HEU, irradiated
May 23, 2010, July 24, 2010, October 10, 2010	Poland, Otwock-Świerk	Russia	S	Fuel of the Maria reactor. MR 36% and 80% HEU fuel.[1012] Three shipments of 43.5 kg each.	130.5 kg of 36% and 80% HEU, irradiated
May 25, 2010	Ukraine, Kiev	Russia	S	Fuel of the VVR-M reactor. VVR-M2 36% HEU and VVR-M5 90% HEU fuel.	55.9 kg of 36% and 90% HEU, irradiated
June 18, 2010	Czech Republic, Rez	Russia	F	Fuel of the LVR-15 reactor. IRT-2M 36% HEU fuel.	4.4 kg of U-235 in 12.2 kg of 36% HEU
October 24, 2010	Belarus, Sosny	Russia	S	Fuel of the Pamir reactor. Pamir 45% HEU fuel.	42 kg of 45% HEU, irradiated
November 29, 2010	Belarus, Sosny	Russia	F	Fresh core of the Pamir reactor. Pamir 45% HEU fuel.	21 kg of U-235 in 46.7 kg of 45% HEU
December 17, 2010	Serbia, Vinca	Russia	S	Fuel of the R-A reactor. TVR-S 80% HEU fuel.[1013]	10.6 kg of U-235 in 13.2 kg of 80% HEU

December 29, 2010	Ukraine, Sevastopol	Russia	F	Fuel of the IR-100 reactor. S-36 36% HEU fuel.	9 kg of U-235 in 25.1 kg of 36% HEU
December 29, 2010	Ukraine, Kiev	Russia	F	Fuel of the VVR-M reactor. VVR-M2 36% HEU and VVR-M5 90% HEU fuel.	About 3 kg of U-235 in 3.3 kg of 90% HEU and 2.3 kg of U-235 in 6.5 kg of 36% HEU[1014]
December 29, 2010, March 21, 2011	Ukraine, Kharkiv	Russia	F	Material stored at the Kharkiv Institute of Physics and Technology. Two shipments—15.7 kg and 108.6 kg of HEU.	About 68 kg of U-235 in 75% HEU and about 12 kg of U-235 in 50 kg of 21–36% HEU[1015]
November 30, 2011	Kazakhstan, Alatau	Russia	F	Fuel of the VVR-K reactor. VVR-K 36% HEU fuel.	11.9 kg of U-235 in 33 kg of 36% HEU
March 25, 2012	Ukraine, Kiev	Russia	S	Fuel of the VVR-M reactor. VVR-M2 36% HEU and VVR-M5 90% HEU fuel.	19.6 kg of 36% and 90% HEU, irradiated
August 13, 2012, October 28, 2012	Uzbekistan, Tashkent	Russia	S	Fuel of the VVR-SM reactor. Two shipments of 36.4 kg HEU each. 108 IRT-3M 36% HEU fuel assemblies and 2 S-36 36% HEU fuel assemblies.[1016]	72.8 kg of 36% HEU, irradiated
September 15, 2012	Poland, Otwock-Świerk	Russia	S	Fuel of the Maria reactor. MR 36% HEU fuel.	61.9 kg of 36% HEU, irradiated
September 22, 2012	Poland, Otwock-Świerk		F	Fuel of the Maria reactor. MR 36% HEU fuel.	9.6 kg of U-235 in 26.8 kg of 36% HEU
December 17, 2012	Hungary, Budapest	Russia	F	Fuel of the ZR-4 critical assembly. About 20% HEU.[1017]	3.4 kg of U-235 in 16.8 kg of 20% HEU
April 5, 2013	Czech Republic, Rez	Russia	S	Fuel of the LVR-15 reactor. IRT-2M 36% HEU fuel.	68.1 kg of 36% HEU, irradiated
July 3, 2013	Vietnam	Russia	S	Fuel of the DNRR reactor. VVR-M2 36% HEU fuel.	11.6 kg of 36% HEU, irradiated
October 7, 2013, October 21, 2013, November 4, 2013	Hungary, Budapest	Russia	S	Fuel of the VVR-SZM reactor. 279 VVR-M and VVR-M2 fuel assemblies.[1018] Three shipments of 16.4 kg each.	49.2 kg of 36% HEU, irradiated
October 21, 2013	Poland, Otwock-Świerk	Russia	S	Fuel of the Maria reactor. MR 36% HEU fuel.	17 kg of 36% HEU, irradiated
September 29, 2014	Kazakhstan, Alatau	Russia	F	Fuel of the VVR-K reactor. VVR-K 36% HEU fuel.	3.7 kg of U-235 in 10.2 kg of 36% HEU

September 29, 2014	Poland, Otwock-Świerk	Russia	S	Fuel of the Maria reactor. MR 36% HEU fuel. Exact amount unknown. About 17 kg of HEU.[1019]	About 17 kg of 36% HEU, irradiated
December 2014	Kazakhstan, Alatau	Russia	S	Fuel of the VVR-K reactor. VVR-K 36% HEU fuel.	36 kg of 36% HEU, irradiated[1020]
September 24, 2015	Uzbekistan, Tashkent	Russia	S	Irradiated liquid fuel of the IIN-3M/Foton reactor.	About 5 kg of 90% HEU, irradiated[1021]
December 22, 2015	Georgia, Tbilisi	Russia	F	Fuel of the PS-1 subcritical assembly.	0.66 kg of U-235 in 1.83 kg of 36% HEU[1022]
September 2016	Poland, Otwock-Świerk	Russia	S	Fuel of the Maria reactor. MR 36% HEU fuel.	61 kg of 36% HEU, irradiated[1023]

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3. Submarine reactors consume about 4.6 tons of HEU of various enrichments, which is equivalent to 1.4 tons of 90% HEU. Civilian ships require about 0.38 tons of HEU (0.23 tons 90% HEU) annually. See Chapter 8 for details.

4. Chapter 7 is based on the paper "Russian/Soviet Nuclear-Powered Fleet", which was prepared by Eugene Miasnikov for the IPFM research report on naval reactor programs. The author would like to thank Vice Admiral (Ret.) Ashot Sarkisov, Adviser to Director of the Nuclear Safety Institute of the Russian Academy of Sciences, and his colleagues Vyacheslav Bilashenko, Pavel Shvedov, and Prof. Sergey Petrov for their helpful comments on the draft paper. The author is also indebted to Rear Admiral (Ret.) Alexei Ovcharenko, whose help was extremely valuable during the work on the project.

5. The 75% and 90% enriched HEU, first obtained in kilogram quantities in the Soviet Union by the end of 1949 and 1952 respectively, was intended for use in one of the early weapons designs. This material was most likely used in experiments at the first critical facility, FKBN, at KB-11 in Arzamas-16 (currently VNIIEF in Sarov) "Минимальная статистика. Производство в СССР атомных бомб, плутония, урана и др. в конце 40-х – начале 50-х годов," October 30, 2014, http://pn64.livejournal.com/42426.html.

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7. Throughout the report, the term low-enriched uranium or LEU refers to uranium with concentration of uranium-235 of more than 0.7% and less than 20%. Highly-enriched uranium or HEU refers to uranium enriched to 20% or more of uranium-235.

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[239] This number does not include the critical assembly associated with the IRT-DPRK reactor in North Korea, as this facility was built without direct Soviet assistance.

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