The Final Stretch: Tackling Remaining HEU Challenges

CNS
OCCASIONAL PAPER
#51 · AUGUST 2021

Miles Pomper, Ferenc Dalnoki-Veress, Margarita Kalinina-Pohl, Artem Lazarev

Middlebury Institute *of* International Studies at Monterey
James Martin Center for Nonproliferation Studies

The Final Stretch: Tackling Remaining HEU Challenges

Miles Pomper
Ferenc Dalnoki-Veress
Margarita Kalinina-Pohl
Artem Lazarev

James Martin Center for Nonproliferation Studies
Middlebury Institute of International Studies at Monterey

460 Pierce Street, Monterey, CA 93940, USA
Phone: +1 (831) 647-4154
Fax: +1 (831) 647-3519

www.nonproliferation.org **www.middlebury.edu/institute**

The authors would like to thank officials from the National Nuclear Security Administration for providing us with their time and their most up-to-date data available on reactor conversions and HEU removals and Scott Roecker and Will Tobey for their comments. We would also like to express our appreciation for funding from the United Kingdom's Department for Business, Energy, and Industrial Strategy, especially the support of Phil Richards and Angus Girling.

Cover image: The facility FRM II, from the IAEA Imagebank via Flickr.

Contents

Executive Summary

Minimizing civil commerce in highly enriched uranium (HEU) has been a longstanding goal of Global Partnership countries, as HEU represents a highly attractive target for terrorists and proliferators.[1] HEU can be used to create the simplest nuclear explosive device, a so-called gun-type weapon. Such a device explosively collides one subcritical piece of HEU with another to form the supercritical mass required for a nuclear detonation. This process is well publicized, and there is consensus among experts that the creation of an improvised nuclear device based on this design is within the technical reach of a financially and organizationally strong terrorist group.[2] To make matters worse, because HEU is only weakly radioactive, it is relatively safe to handle and hard to detect. Even HEU waste is less radioactive than one might hope from a security-oriented standpoint. In a matter of months, HEU waste quickly loses its "self-protection," in that it will not give an incapacitating radiation dose to a would-be thief.[3]

HEU's primary civilian use is in research reactors, which carry out a range of functions from education and basic scientific research to producing medical isotopes and "doping" silicon for semiconductors. Moreover, in the words of a 2016 U.S. National Academy of Sciences study, "Other mechanisms for producing neutrons with similar spectra and flux levels to fulfill these missions do not currently exist."[4]

---

[1] How much HEU would be needed would depend on the enrichment level of the HEU, the design and makeup of the weapon, and the expertise of the bomb builders. Without a reflector and at normal density, a sphere of pure U-235 would be just critical at 50 kilograms, i.e., just on the verge of a chain reaction. Therefore, weapon-grade HEU (90 percent) would be critical at roughly 56 kilograms without any compression or collision. A 1998 study by Los Alamos National Laboratory concluded that roughly 20 kilograms of 94-percent enriched HEU would be one critical mass if a four-inch reflector of natural uranium was used. Joseph L. Sapir, Russell Kidman, and R. W. Brewer, "235U (94%) Spheres Surrounded by Natural-Uranium Reflectors," http://lib-www.lanl.gov/la-pubs/00418688.pdf. States, which can use implosion technology to increase the density of the HEU, can use much less material. For safeguards purposes, the IAEA very conservatively estimates a "significant quantity of HEU" (that is the material that a state actor would need for a first nuclear weapon) as 25 kilograms of U-235. For useful discussions see Annette Schaper, *Highly Enriched Uranium: A Dangerous Substance That Should Be Eliminated,* Report No. 124, Peace Research Institute Frankfurt, 2013, 3–6, http://www.hsfk.de/fileadmin/downloads/prif124.pdf, and Alan J. Kuperman, ed., *Nuclear Terrorism and Global Security: The Challenge of Phasing Out Highly Enriched Uranium* (Abingdon, UK: Routledge, 2013), 4–5.

[2] Charles D. Ferguson, William C. Potter, *The Four Faces of Nuclear Terrorism* (New York: Routledge, 2005), 134.

[3] C. Hansell and F. Dalnoki-Veress, *Examining Self Examining Self-Protection Protection Requirements: Methods Requirements: Methods to Improve the Security to Improve the Security of HEU Materials,* Presentation at the Presentation at the International Symposium on Nuclear International Symposium on Nuclear Security Vienna, April 2, 2009.

[4] National Academies of Sciences, Engineering, and Medicine, Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors (Washington, DC: The National Academies Press, 2016), 2.

The international community has made significant progress during the last decades in converting such reactors from HEU to LEU fuels. Thirty-three countries and Taiwan have been cleared entirely of HEU, including 15 since the Obama administration launched the Nuclear Security Summit process in 2010.[5] More than 100 reactors have either been shut down or converted since the U.S Reduced Enrichment for Research and Test Reactors (RERTR) program began. Nearly 7 tons of HEU have been removed from civilian use.[6] These efforts have strengthened the nonproliferation and nuclear security regimes and decreased the threat from HEU misuse worldwide.

The Chairs Summary of the Third International Symposium on HEU Minimization, sponsored by Norway and the IAEA concluded, “While challenges remain, significant progress has been made … Most countries, and complete regions of the world, are today HEU-free.”

The United Kingdom has long been a key supporter of HEU minimization efforts, including providing substantial funding as well as signing on to a number of international commitments in this regard including an HEU gift basket at the 2016 Nuclear Security Summit committing to the eventual elimination of HEU in civilian use. Under a bilateral agreement, the United Kingdom also transferred a record amount of HEU—-nearly 700 kilograms—to the United States in 2016. Her Majesty’s government has made a reinvigoration of global HEU minimization efforts a cornerstone of its chairmanship of the Global Partnership in 2021.

Nonetheless, dozens of tons of HEU are still in civilian use worldwide, with more than 80 reactors still using HEU (see Appendix 3) Remaining challenges include:

- **The need to strengthen international commitments.** Less than two dozen countries—including the UK have made firm commitments to minimize and eliminate civil HEU. Many possessors have still failed to do so.

- **Political problems.** Political challenges in Pakistan, Iran, and Syria have hampered efforts to convert the last HEU-fueled Miniature Neutron Source Reactors (MNSR) exported by China. Meanwhile, the political crisis in Belarus has placed another

[5] Communication with National Nuclear Security Administration, March 10, 2021.
[6] Communication with National Nuclear Security Administration, March 25, 2021. NNSA officials indicated that as of that date 6,810.6 kg had been removed or downblended—including 1,633.5 kg of US-origin, 2,282.3 kg of Russian-origin, and 2,894.8 kg of “gap material’ from other countries.

obstacle in efforts to convert facilities there to full LEU use, while South Africa continues to hold onto sizeable stocks of HEU as a tool of its disarmament diplomacy.

- **Technical obstacles.** While the United States and European states have made significant progress recently in developing high-density LEU fuels to convert their most challenging high-performance reactors, further work is required and will demand consistent financial support and political backing for nearly two decades more.

- **Slow progress in shutting down or converting Russia's HEU reactors.** Russian reactors now represent more than half the world total. While a half-dozen HEU-fueled reactors have shut down since 2016, Russia has just begun operating the world's lone new HEU-fueled reactor.

- **Potential HEU use in deep space missions.** As discussed below, there is a resurgence in interest in using fission reactors for deep space missions for propulsion and for providing power on the Moon or Mars. Some of these HEU-fueled reactors could require dangerous amounts of weapon-grade HEU (i.e, far in excess to what is needed for a nuclear weapon).

- **Declining international attention.** Political attention to HEU conversion has slipped sharply since the end of the Nuclear Security Summit process.

As the Oslo symposium report noted: Further minimization requires sustained technical, financial and political commitment. International cooperation is crucial."[7] We recommend that Global Partnership governments support the following steps:

- **Reinvigorate Efforts to Form HEU Free Zones**: In the run-up to the 2016 Nuclear Security Summit, there were serious discussions about establishing formal HEU-free zones in regions such as Latin America and Southeast Asia which had been cleared of HEU, or Central and Eastern Europe which were close to achieving that goal.[8] Those efforts should be reinvigorated.

- **Neutron Needs Study**: Encourage the International Atomic

[7] Chairs Summary, Third International Symposium on HEU Minimization, Oslo, June 5-7, 2018.
[8] Miles A. Pomper, Andrew J. Bieniawski, and Elena Sokova, T*he Case for Highly Enriched Uranium-Free Zones*, Nuclear Threat Initiative, June 2015. https://media.nti.org/pdfs/The_Case_for_Highly_Enriched_Uranium-Free_Zones_Final.pdf

Energy Agency to conduct a global study assessing research reactor needs for the 10-, 20-, and 50-year increments. This study could help determine whether additional HEU-fueled reactors can be shut down without sacrificing scientific research or other peaceful applications.[9]

- **CPPNM "Gift Basket" on High-Performance Reactor Conversion**; Commit to Maintain Current Effort at Converting High-Performance Research Reactors to LEU: Countries could bring a "gift basket" to the 2022 Review Conference of the amended Convention on the Physical Protection of Nuclear Material (CPPPM/A) pledging to maintain funding and research to convert these reactors to LEU. A regular high-level group similar to the recently terminated High-Level Group on the Safety and Supply of Medical Radioisotopes (HLG-MR) could be established to measure and chart progress.

- **INFCIRC 912**: Encourage Additional Countries to Join INFCIRC 912 (HEU "Gift basket") by the CPPNM/A Review Conference. Several countries did not join the gift basket at the NSS launch because the still had HEU-based operations to convert, such as Belgium, France, and Germany. Others were not participants.

- **MNSR Conversion**: First, leverage the Global Partnership to raise funds and apply political pressure for the conversion of Miniature Neutron Source Reactors in Pakistan, Syria, and Iran. Secondly, hold a technical workshop in Vienna in partnership with the IAEA that shares lessons learned from MNSR conversions in Africa as a potential model for Iran, Pakistan, and Syria. This can be done in the form of a technical workshop organized in Vienna.

- **Reinvigorate US-Russia cooperation**—Since 2014, US-Russian nuclear security cooperation has been hampered by US congressional restrictions and Russian disinterest. But with Russia as by far the biggest holder of civilian HEU, cooperation is essential and should be revived beginning with removal of HEU in Belarus. Other issues related to joint development of high-density LEU fuels and potential LEU Russian exports could then be discussed.

[9] For background, see Julia Phillips, Miles A. Pomper, and William Tobey, "How to Make Sure Neutrons Save Lives Instead of End Them," *The Bulletin of the Atomic Scientists,* May 12, 2021 https://thebulletin.org/2021/05/how-to-make-sure-neutrons-save-lives-instead-of-end-them/

- **Take South African spent HEU**—Discussions should be revived on an agreement to remove South Africa's spent HEU fuel from domestic sources.

- **US Certification to Block HEU exports for Mo-99**: The Biden administration will have to decide in 2022 whether to continue to waive restrictions on US exports of HEU for Mo-99 production. Given recent progress, it should not do so and certify that sufficient LEU Mo-99 is available to meet medical needs. At the same time, Global Partnership countries should work to encourage medical authorities to license LEU-based Mo-99 such as material supplied by Belgium in order to hasten the conversion process.

- **International Attention**: To maintain focus, the UK and other Global Partnership countries should press the issue at relevant international gatherings, such as the NPT Review Conference, and Norway should be encouraged to continue its practice of hosting international symposium every six years (ie in 2024) to discuss and chart progress.

- **Strengthen restrictions on HEU use in space.** The Trump Administration wisely issued a directive to restrict (but not ban) HEU use in future space missions. This directive should be strengthened to make it explicit that HEU should not be used and only waived unless there is proof that feasible alternatives do not exist. A request for such a waiver should be reviewed by an independent technical team at the financial expense of the relevant agency. The Biden Administration should reaffirm the Trump Administration's directive and other countries should enact similar policies.

Background

The use of HEU worldwide began as part of the US Atoms for Peace program in the late 1950s, along with a similar Soviet initiative.[10] However, India's "peaceful nuclear explosion" in 1974 raised concerns about the potential misuse of exported HEU and led the international community to reconsider additional transfers.

By 1978, Washington and Moscow had launched fledgling efforts to reduce HEU use overseas (and in the US case, also domestically).[11] In the United States, these efforts were further bolstered by the 1992 Schumer Amendment to that year's Energy Policy Act. This measure restricted US HEU exports to reactor operators who could not use LEU fuel or targets and had committed to transition from HEU once a low-enriched substitute became available, and to cases where the United States was in the process of developing such a substitute.

These HEU minimization initiatives were intensified in the aftermath of the September 2001 terrorist attacks in the United States, which drove home the threat of nuclear terrorism. Subsequently, the George W. Bush administration consolidated a number of existing programs and, with the support of Congress, boosted funding for these efforts and expanded their scope to take in additional types of facilities and materials. The Bush administration also fostered bilateral cooperation with Russia. Presidents Bush and Vladimir Putin reached an agreement in 2005 whereby both countries pledged to provide LEU for any US- or Russian-designed research reactor currently operating with HEU and whose operators were willing to convert. Spent or remaining fresh HEU would then be repatriated to its country of origin. In practice, this meant that the US National Nuclear Security Administration (NNSA) paid Russia to help ship back HEU to Russia from countries such as Poland, Serbia, and Ukraine.

In a 2009 speech in Prague, President Barack Obama announced, "a new international effort to secure all vulnerable nuclear material around the world within four years."[12] Obama said the United States "will set new standards,

[10] US Nuclear Regulatory Commission, *The United States Nuclear Regulatory Commission's Report to Congress on the Disposition of Highly Enriched Uranium Previously Exported from the United States.* January 1993.
[11] Anya Loukianova and Cristina Hansell, "Leveraging U.S. Policy for a Global Commitment to HEU Elimination," in *The Global Politics of Combating Nuclear Terrorism: A Supply-Side Approach,* eds. William C. Potter and Cristina Hansell (Abingdon, UK: Routledge, 2010), 33–34.
[12] President Barack Obama, "Remarks by President Barack Obama, Hradcany Square," speech, Prague, Czech Republic, April 5, 2009, http://www. whitehouse.gov/the_press_office/Remarks-ByPresident-Barack-Obama-In-Prague-As-Delivered.

expand our cooperation with Russia, pursue new partnerships to lock down these sensitive materials."[13]

Obama's effort also helped foster an international consensus on the need to minimize (but not eliminate) the civilian use of HEU. The issue was taken up at a UN Security Council summit held in September 2009 that Obama chaired. Resolution 1887, which was unanimously adopted at that meeting, called on states to "manage responsibly and minimize to the greatest extent that is technically and economically feasible the use of highly enriched uranium for civilian purposes, including by working to convert research reactors and radioisotope production processes to the use of low enriched uranium fuels and targets."[14]

The Obama administration also reinvigorated efforts to end HEU in medical isotope production (detailed below) with the American Medical Isotope Production Act, which sought to phase out worldwide use of HEU in medical isotope production by 2020, a deadline which was largely reached.[15] In June 2012, the Obama administration made clear its explicit goal of eliminating HEU in civil use: "The United States is committed to eliminating the use of HEU in all civilian applications, including in the production of medical radioisotopes, because of its direct significance for potential use in nuclear weapons, acts of nuclear terrorism, or other malevolent purposes."

Considerable progress was made during the 2010-2016 Nuclear Security Summit (NSS) process which helped clear some longstanding political roadblocks to HEU removals and channel this new support into fresh commitments. For instance, at the 2014 NSS, the final communiqué encouraged "states to continue to minimize the use of HEU through the conversion of reactor fuel from HEU to LEU, where technically and economically feasible, and in this regard welcome cooperation on technologies facilitating such conversion."[16] The summits also produced important communiqué language and joint commitments ("gift baskets") to convert from using HEU in medical isotope production and cooperate on new non-HEU fuel development.

A final 2016 HEU joint statement by 22 countries, including the United States and the United Kingdom declared that "HEU minimization – and ultimate elimination of HEU use in civilian applications – should continue to be a top priority for all States that continue to possess HEU." In that statement, the signatories pledged to "Convert or shut down all HEU civilian reactors, including

---

[13] Ibid.
[14] United Nations Security Council, Resolution 1887 (2009), September 24, 2009, S/RES/1887 (2009), para. 25, p. 5, at: http://www.un.org/News/Press/ docs/2009/sc9746.doc.htm.
[15] The American Medical Isotopes Act of 2012, at: http://www.gpo.gov/fdsys/pkg/PLAW112publ239/html/PLAW-112publ239.htm.
[16] https://2009-2017.state.gov/documents/organization/237002.pdf

research reactors, critical assemblies, subcritical assemblies, pulsed reactors, and fast reactors, as soon as economically and technically feasible" and to "Continue to support and foster the development and qualification of high-density LEU fuels including multinational cooperation programs."[17] Notable non-signatories among summit participants included Belgium, France, Germany, and Pakistan, all of which have HEU-fueled reactors. (Russia, which houses the largest number of HEU fueled facilities, did not attend the 2016 NSS). After the NSS process concluded Norway, its lead sponsor, encouraged all IAEA member-states to sign up to the commitments by circulating the gift basket text as an IAEA Information Circular (INFCIRC 912).[18]

Perhaps the most tangible accomplishment of the summits was to push individual countries to move ahead with converting reactors from HEU and sending that material to the United States or Russia. For example, the United States had been pressing to clear Ukraine of HEU for nearly two decades, but it was only the political leverage of the summit process that finally accomplished this goal in 2012.

This progress has continued, but at a considerably slower pace since the summits. In one notable milestone, all Canadian-designed SLOWPOKE reactors have now been converted to LEU or shut down with the closure of reactors in Saskatchewan and Alberta.[19] Similarly, two Chinese-designed Miniature Neutron Source Reactors (MNSRs) in Ghana and Nigeria—which are very similar to SLOWPOKE reactors—have been converted, as well as one reactor in Kazakhstan.

[17] https://static1.squarespace.com/static/568be36505f8e2af8023adf7/t/56febac0b654f939134d97d1/1459534530157/HEU+Minimization+Gift+Basket+for+NSS+2016.pdf
[18] https://www.iaea.org/sites/default/files/publications/documents/infcircs/2017/infcirc912.pdf
[19] Seven HEU-fueled SLOWPOKE (Safe Low Power Kritical Experiment) –2 reactors were built –six in Canada and one in Jamaica. The Jamaican reactor and one at the Polytechnique Montreal have been converted to LEU; the other five SLOWPOKEs have been decommissioned. One Slowpoke-2 reactor at the Royal Military College always operated on LEU. https://www.rmc-cmr.ca/en/chemistry-and-chemical-engineering/slowpoke-nuclear-reactors-canada and continues to operate.

High Performance Reactors-A Technical Challenge

A key technical obstacle to further progress has been that some high-performance reactors (HPRR) in the United States and Europe cannot convert with existing fuels, and new fuels must be developed. As one of us previously has noted “converting reactors is a time consuming and technically demanding process akin to using a new kind of fuel in a car engine while seeking to maintain the car’s performance and safety and not altering its basic dimensions or operating costs.”[20] In the case of high-performance reactors this is equivalent to carrying out engine conversions on a Mercedes or Ferrari.

The starting point for this challenge is finding ways to increase the uranium density of the material. Generally, to maintain the same research reactor performance parameters with LEU fuel, fuel designers must increase uranium density in proportion to the decrease in enrichment and then add a further small density increase to make up for the so-called “neutron intensity penalty.”[21] As a result, substituting 20% enriched LEU for the weapon-grade 90% enrichment HEU typically used in current HPRR fuel elements requires 6.5 times the amount of uranium (see Figure 1).

Moreover, one of the requirements of successful conversion is to ensure that no major structural changes occur to the reactor so that existing experiments and beamlines are not affected. For new LEU fuel to be qualified it must maintain the same mechanical and geometric integrity. The cladding must provide the same barrier and cooling paths must not be significantly affected. As a result, U.S. and European scientists have been working for decades to develop appropriate high-density LEU fuels that might be substituted for the current HEU fuels used in HPRRs. Unfortunately, it has been a challenging task and the timetable for converting the most challenging reactors, initially expected to occur by 2013 is now scheduled for 2035.[22]

---

[20] Miles A. Pomper, *The 2012 Seoul Nuclear Security Summit and HEU Minimization,* US-Korea Institute at SAIS working paper, January 2012, at: uskoreainstitute.org/wp-content/uploads/2012/01/ USKI_NSS2012_Pomper.pdf.

[21] The “neutron intensity penalty” corresponds to a decrease in neutron intensity due to higher fraction of neutrons absorbed since there is a higher U-238 content at low enrichments. Frank vonHippel, *Banning the Production of Highly Enriched Uranium,* International, Panel on Fissile Materials, March 2016, p. 26.

[22] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors,* National Academies of Science, 2016. www.nap.edu/catalog/21818/reducing-the-use-of-highly-enriched-uranium-in-civilian-research-reactors. Discussion with NNSA officials.

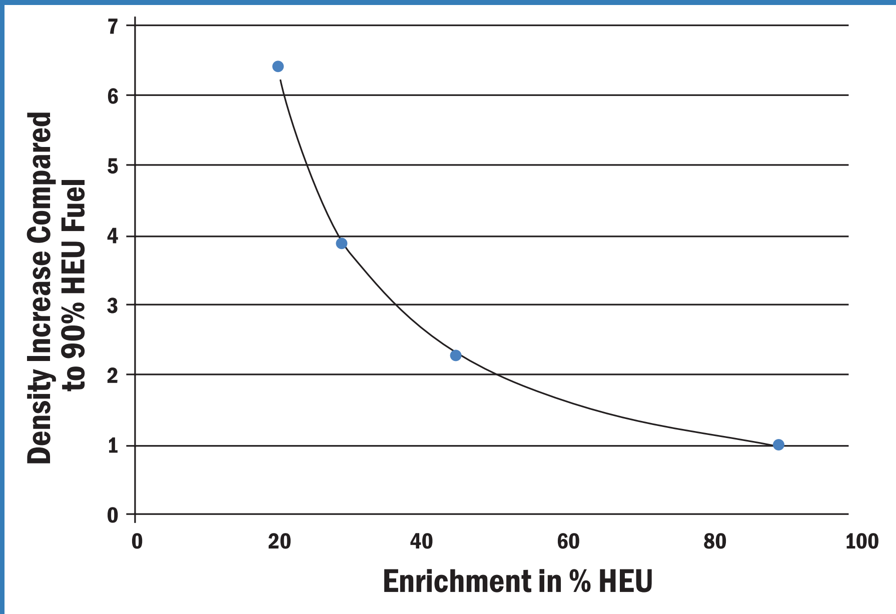


Figure 1
The increase in density compared to the density at 90% enriched fuel for the RHF reactor as calculated by Mo and Matos.[23] Notice that the density increases when the enrichment is lowered, this is because more U-235 is needed to keep the total quantity of U-235 the same.

Technical Challenges of Converting High Performance Research Reactors

Developing the high-density LEU fuels required for conversion has been a transatlantic engineering challenge. The problem is that uranium exists in several crystallographic forms, which have different dimensions and structures, resulting in varying resilience to irradiation. The only form where uranium remains stable under irradiation is the gamma phase but this form is only stable above 776^{o}C.[24] The gamma phase breaks down (decomposes into different crystallographic forms) at lower temperatures to other crystallographic forms. This instability results in swelling of the fuel meat and local deformations in the dimensions ("pillowing") of the fuel cladding under irradiation. If the swelling and displacement is too great, it risks damage to the cladding and the release of radioactive fission products. However, the decomposition reaction is suppressed when uranium is alloyed with certain metals making the fuel robust against thermal cycling and irradiation.[25] Several metals have been assessed as candidates, but molybdenum has been chosen since it has optimum mechanical properties and corrosion resistance and is stable in the gamma phase. Choosing the optimal proportion of molybdenum is a tradeoff between low fractions to minimize neutron absorption by molybdenum, and high fractions to stabilize the fuel under irradiation.[26]

[23] http://www.rertr.anl.gov/LEUCONVS/RHF89.pdf
[24] The gamma phase is a particular crystalline phase of the uranium molybdenum alloy.
[25] Unalloyed uranium exists in three allotropic forms of which the body centered cubic (gamma phase) is the most stable but normally only occurs at high temperatures.
[26] Meyer, M. K., J. Gan, J. F. Jue, D. D. Keiser, E. Perez, A. Robinson, D. M. Wachs, N.

There are two principal fuel types that the United States and Europe have focused on for development. U.S. researchers have focused on monolithic uranium-molybdenum (U-Mo) fuels; that is fuels where all the meat is a uranium molybdenum alloy. European scientists have primarily focused on developing U-Mo dispersion fuels where globules of U-Mo alloy are interspersed in an aluminum matrix. The difference between the two fuel types is shown in Figure 2. The dispersion fuels use U-6Mo or U-7Mo (meaning uranium alloy with 7% by weight molybdenum) while monolithic fuels under development tend to use a higher molybdenum fraction of U-10Mo.

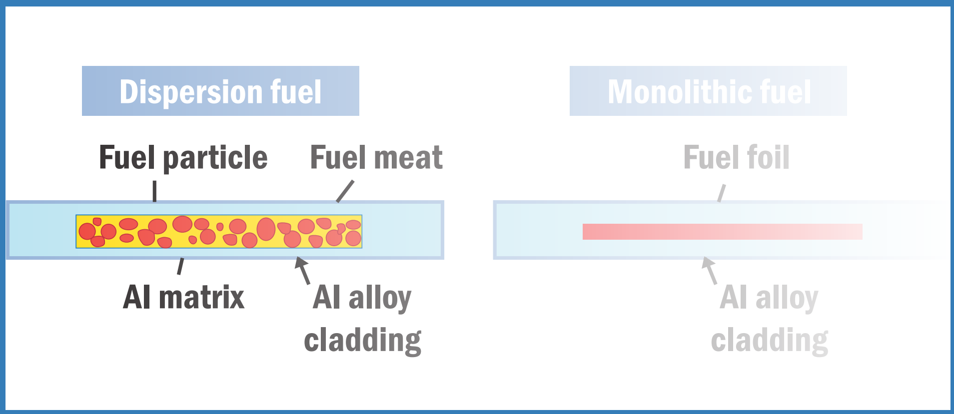


Figure 2:

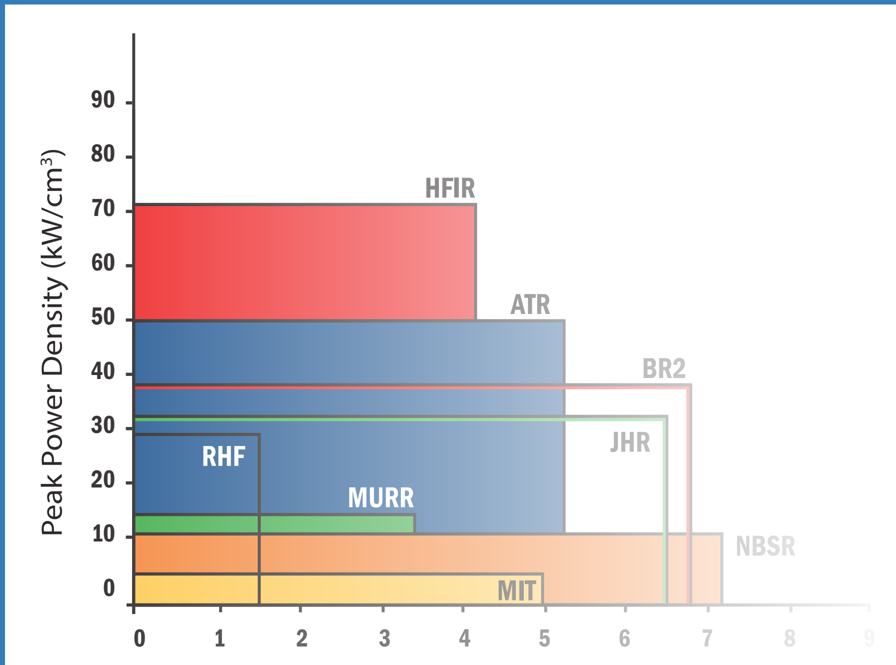
Schematic cross sections of (a) plate-type dispersion fuel and (b) plate-type monolithic fuel.[27]

Each HPRR has specific performance requirements for safe and expected peration of the reactor that are quantified in terms of two parameters that range from zero to specific maximum values (*known as the performance envelope*) that should not be exceeded. These are the local *power density* of the fuel and the *fission density*. The fission density is proportional to the fraction of the uranium-235 used (burnup) and “provides a measure of the accumulated fission products and fission gases and radiation damage that can lead to failure of the fuel.”[28] The power density is related to the neutron flux which is a measure of the utility or capability of the reactor. The two specifications thus are different for different reactors and describe the performance the fuels must meet to fulfill reactor operator objectives (see Figure 3 for the performance envelopes of various high-performance reactors).

Woolstenhulme, G. L. Hofman and Y. S. Kim, “Irradiation performance of U-Mo monolithic fuel,” *Nuclear Engineering and Technology* 46, no. 2 (2014): 169-182.

[27] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors,* National Academies of Science, 2016, p. 62, at: www.nap.edu/catalog/21818/reducing-the-use-of-highly-enriched-uranium-in-civilian-research-reactors.

[28] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors,* National Academies of Science, 2016, at: www.nap.edu/catalog/21818/reducing-the-use-of-highly-enriched-uranium-in-civilian-research-reactors.



density of 40 kW/cm^3.

European HPRR's: Recovering from "Unexpected" Technical Challenges

Developing high-density fuel for any high-performance reactor is an ambitious undertaking. Throughout the years, European investigators have formed several consortia to tackle the task (ALPS from 2008-2013, LEONIDAS from 2010-2014, HERACLES from 2013-2020, and now LEU-FOREVER [an EU initiative to study uranium silicide (U_3Si_2) as a fuel]). HERACLES is a collaboration of German, French and Belgian researchers to develop high density HPRR fuels. European efforts in the words of one recent retrospective "experienced a number of unexpected setbacks."[29] This section will discuss some of these challenges and recent progress in addressing them.

Early experiments in 2003 irradiated two flat plates ("FUTURE" test) in the BR-2 reactor with U7Mo (7% U by weight) atomized powder and found that as the burnup (expressed as the peak fission density in Figure 1) increased to about 2e21 fissions/cm^3, fuel plate swelling occurred. Large voids formed between the U-Mo kernels and the aluminum matrix, accounting for as much as 70% of the volume. Several solutions were suggested to suppress the interaction such as the addition of silicon to the aluminum matrix or adding a protective layer of zirconium around the U-Mo kernels. These solutions reduced the swelling, allowing a maximum burnup of up to 4.7×10^{21} fissions/cm^3 to be reached. However, the improvement did not reach a required burnup of 6.8×10^{21} fissions/cm^3. It was recognized that the reason for the

[29] Van den Berghe, S. and Lemoine, P., "Review of 15 years of high-density low-enriched UMo Dispersion fuel development for research reactors in Europe," Nuclear Engineering and Technology, 46(2), 2014, pp.125-146.

rapid swelling was because of the process of recrystallization, where gas bubbles form and eventually coalesce to form larger bubbles.

To suppress these effects and improve fuel plate resilience, the HERACLES group conducted additional fuel plate irradiation experiments where the U-Mo dispersal fuel was annealed (heated and slowly cooled to remove stresses).[30] This set of experiments took place over the last few years and are known as EMPIrE and SEMPER FIDELIS. In the EMPIrE experiment, 48 mini-plates were irradiated in the US ATR reactor to study variability in "fabrication and irradiation conditions" and included the performance envelope of the BR2 and RHF reactors. Results from non-destructive post-irradiation examinations (PIE) indicated "good performance" for all variants while destructive PIE is still under study. In the case of SEMPER FIDELIS a full-size plate was irradiated at the BR2 reactor. According to a DOE report the experiment had some setbacks with "faulty irradiation device design that led to damage of a number of the plates before they reached their target burnups." However, one plate did reach a burnup 80% of the power levels that envelope BR2 and RHF reactors and the PIE indicated that the performance of that plate was "favorable".[31]

Other recent irradiation experiments on U_3Si_2 dispersion fuel are either in the process of being carried out or the results are being analyzed. The first experiment, COBRA-FUTURE, tested a full-size LEU element manufactured in the United States at the BWXT; the element was irradiated at Belgium's BR2 reactor in 2020. The other experiment, HiPROSIT, also took place at the BR2. This full-size plate experiment tested various high-density fuel fabricated by CERCA with loadings ranging from 4.8-5.6 gU/cm^3. This experiment is part of the LEU-FOREVER consortium to investigate the utility of U_3Si_2 fuel for European HPPR in contrast to using U-Mo. An early result was reported at the 2021 RERTR conference in late April showing fuel swelling as a function of the burnup for the U_3Si_2 fuel element (see Figure 4 below).[32]

---

[30] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors,* National Academies of Science, 2016. www.nap.edu/catalog/21818/reducing-the-use-of-highly-enriched-uranium-in-civilian-research-reactors

[31] Birgeneau, Robert, Sue Clark, Pengcheng Dai, Thomas Epps, Karsten Heeger, David Hoogerheide, Marc Kastner et al., *The Scientific Justification for a US Domestic High-Performance Reactor-Based Research Facility,* (2020).

[32] Sven van den Berghe, HERACLES/LEUFOREVER Campaign Progress and Plan, Virtual Presentation at RERTR 2021, April 22, 2021.

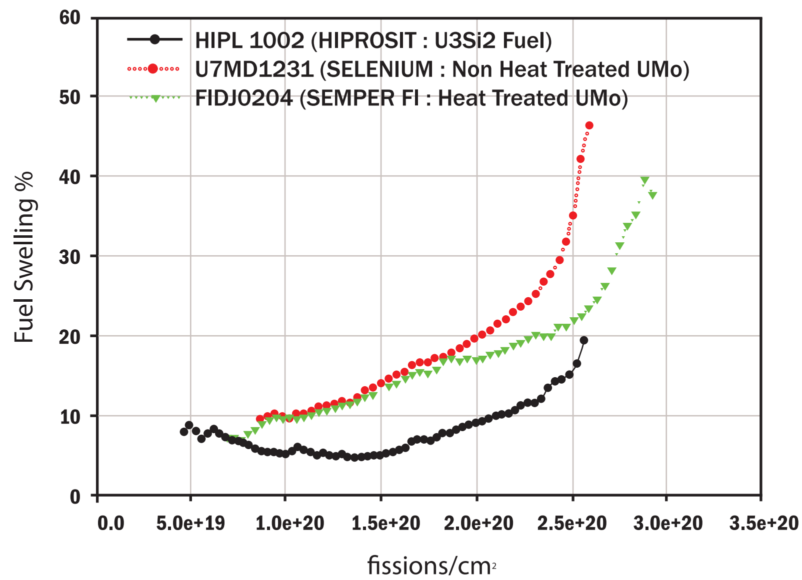


Figure 4

Fuel swelling as a percentage plotted against the number of fissions per cm^2 for three types of fuel, heated and non-treated U-Mo dispersion fuel and U_3Si_2 fuel. The fissions/cm^2 rather than the usual fissions/cm^3 was chosen for the absissa, because of the different geometries and densities of the different fuels the most appropriate way to compare the behavior is to plot the data in terms of the fissions/cm^2. We see that while this data is preliminary and needs to be analyzed further, it does indicate that U_3Si_2 is a good candidate fuel just in terms of when 10% or 20% swelling is reached as a function of burnup. The same is true for fuel plate swelling which had a similar behavior.[33]

What researchers found for the U_3Si_2 fuel is encouraging, fuel swelling first dips down for U_3Si_2 and then increases. This contrasts with UMo fuels where the swelling consistently increases and crosses the 10% and then 20% swelling thresholds sooner than the U_3Si_2 fuel. Although this data is preliminary, it does indicate that fuel swelling is suppressed for U_3Si_2 fuels equivalent to or better than the UMo fuels. The fuel swelling for various fuels is shown for two different thresholds in Figure 5 where the data is extracted from Figure 4.

The full regulatory qualification process requires irradiating several plates in the reactor core along with a mixed fuel element containing standard HEU fuel and LEU fuel. In addition, a further complication is that the licensing of the fuel will be different for different reactors and regulatory bodies. Therefore, it is expected that the full testing program will extend at least until 2027 for U-Mo dispersion fuel and the fuel will not be available until 2031-2036.[34] At

[33] This graph is adapted from the slides presented by Sven van den Berghe from the Belgium Center for Nuclear Research (SCK-CEN) and was annotated to indicate the type of fuel. Sven van den Berghe, HERACLES/LEUFOREVER Campaign Progress and Plans, Virtual Presentation at RERTR 2021, April 22, 2021.

[34] Further explanation on the 7-year delay was given by the study director (J. Heimberg) in an email to the authors: "Qualification, licensing, and conversion account for the time between 2027 and "20 years" (2035)—although it was difficult to obtain exact estimates on the length of each of these since the reactors slated for conversion span multiple licensing agencies and countries and some of the reactors' conversion timelines may be longer than others based on

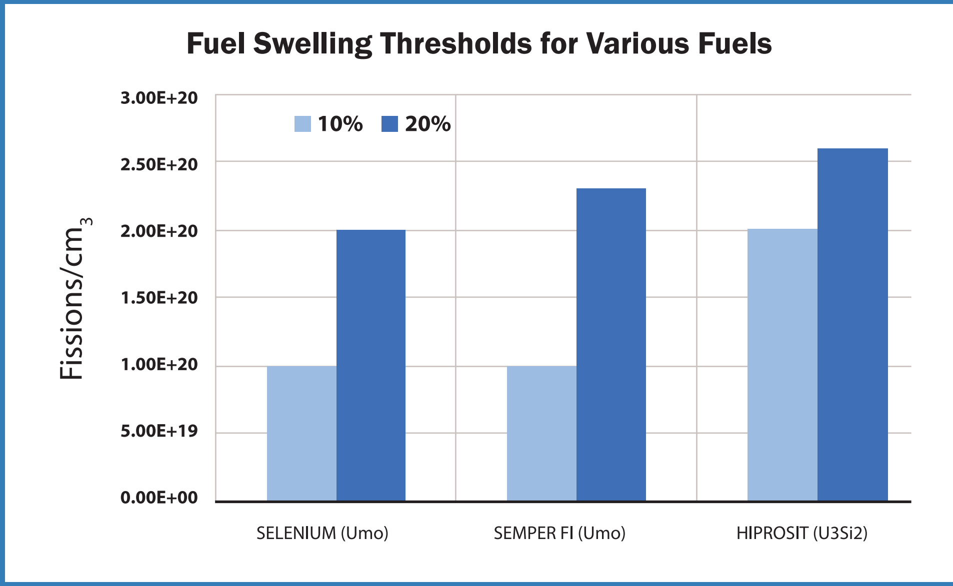


Figure 5

Fuel swelling for various fuels for two different swelling thresholds. Note that the data is taken from the data in Figure 4.

the April 2021 RERTR Meeting the schedule presented a more optimistic schedule suggesting that all testing, PIE and non-destructive testing for all fuels, will be completed by 2024.[35]

their core designs."

[35]Sven van den Berghe, HERACLES/LEUFOREVER Campaign Progress and Plans, Virtual Presentation at RERTR 2021, April 22, 2021.

European High-Performance Research Reactors

U.S. policy on providing fuel for European reactors is dictated by the 1992 Schumer Amendment which forbids U.S. exports of HEU unless countries have pledged to convert or are in the process of doing so. This amendment provides important leverage to support NNSA's efforts to convert the reactors to LEU.

There are four European high-performance research reactors that are unable to convert with currently available fuels. They are the FRM-II in Germany, the BR-2 in Belgium, and the HRF & JHR reactors in France. The first three reactors have been able to receive HEU from the United States pending conversion. FRM-II operators, at the University of Munich in Garching, have circumvented US restrictions by obtaining HEU fuel from Russia.

See Appendix 1 for the HEU shipments that have taken place from the United States NNSA/Y-12 National Security Complex to Europe and other countries since 2008. Please see reactor specific discussions below for the specifications and current status of the reactors and on efforts by the reactor operators to procure HEU.

Forschungs-Neutronenquelle Heinz Maier-Leibnitz-II Reactor (FRM-II): U-10Mo Fuel

Constructed in 2004, the FRM-II is operated and managed by the Technische Universität München (TUM). The FRM-II has five neutron beam irradiation facilities and more than 30 instruments in operation or under construction. Most researchers are engaged in basic science but applied science is conducted as well. The reactor also has a medical facility that uses fast neutrons to destroy tumors near the skin.[36]

The history of the FRM-II reactor is particularly disturbing as it was built after a de facto global moratorium on building new reactors using HEU fuel was in place. The reactor is fueled with 93% HEU even though eight years before first criticality Argonne National Labs had proposed an alternative design which used LEU instead. Furthermore, the Bavarian government set the bar for conversion so high (a performance reduction of less than 5% and no modifications to the core structure) that it has required decades of research to find fuel to satisfy these objectives.[37] FRM-II is one of the few research reactors in Europe that still uses HEU fuel.

[36]https://www.frm2.tum.de/en/industry-medicine/radiation-therapy-of-malignant-tumours/
[37]A. Glaser, *Bavaria Bucks Ban,* Bulletin of Atomic Scientists, March/April 2002.

To respond to pressure from the international community, the German government had promised to convert the FRM-II to 50% HEU by 2010. However, as this initial deadline approached, Berlin opted to postpone any action and extend the deadline again until 2018.[38] Furthermore, in July 2016, Russia confirmed that it is supplying HEU for the FRM-II undercutting US efforts to leverage its control over HEU exports to pressure Germany into conversion.[39] Still the United States and domestic groups, continued to press for conversion of the reactor. In October 2019, the Green party parliamentary faction, which had recently become the second largest regional party, petitioned the Bavarian Ministry of Environment and Consumer Protection to block operation of the facility until it converted to fuel with less than 50 percent U-235.[40] Months later, in May 2020, French company Framatome and the Technical University of Munich (TUM) announced that they will work together for the "commercial development of uranium-molybdenum fuel (U-Mo) for nuclear research reactors." The line is expected to produce the first fuel elements for irradiation experiments in 2022.

The 2020 press release stops short of officially stating that the focus is to produce LEU fuel for the FRM-II reactor.[41] Still, development of an LEU U-Mo fuel could allow the FRM-II reactor in Munich to be converted. In July 2019, Chris Landers who manages the conversion program at the NNSA stated that: "All parties agreed to develop a technical program between FRM II and U.S. national laboratories, as well as to establish a government-to-government oversight group to help achieve a successful conversion of the FRM II reactor." In fact, according to the NNSA, TUM management must submit a report this year explaining how they will convert the reactor to run on fuel with an enrichment below 40%. While this still does not constitute LEU, it is a step in the right direction and is consistent with Recommendation 4a in the National Academies 2016 report on reactor conversion.[42] [43]

---

[38] A reduction to 50% HEU is a significant technical step but still poses a security threat.
[39] Pavel Podvig, "Russia Confirmed Supplying HEU to the FRM-II reactor in Germany," International Panel on Fissile Materials, July 18, 2016. http://fissilematerials.org/blog/2016/07/russia_confirmed_supplyin.html
[40] https://www.frm2.tum.de/en/news-media/press/news/news/article/gutachten-zur-rechtmaessigkeit-des-betriebs-des-frm-ii-mit-hochangereichertem-uran-heu0/
[41] https://world-nuclear-news.org/Articles/Framatome-TUM-to-develop-new-research-reactor-fuel
[42] Private discussions with NNSA personnel.
[43] National Academies of Sciences, Engineering, and Medicine. Reducing the use of highly enriched uranium in civilian research reactors. National Academies Press, 2016.

Jules Horowitz Reactor (JHR): HEU U_3Si_2 Dispersal Fuel Initially U-7Mo Later

The JHR is a 100 MW French reactor under construction at CEA Caderache, expected to begin operating in 2025/27.[44] The purpose of the reactor is to test materials as well as to produce medical isotopes. The JHR's planned LEU fuel is U-7Mo, a fuel with a uranium density of 8gU/cm^3. It is the only reactor that is likely to utilize U-7Mo. The RHF and the BR-2 are likely to use U_3Si_2 and the FRM-II is expected to rely on U-10Mo monolithic fuel.

However, an independent review in 2015 suggested that JHR operators consider uranium silicide dispersion fuel as a "backup" to the development of U-7Mo dispersion fuels. The primary reason why U_3Si_2 is being considered as a viable fuel for the JHR and other European high flux reactors is that other high flux reactors (with peak fluxes as high as 10^{14} n.cm^{-2}.s^{-1}) have been converted using this fuel such as the HFR Petten, SAFARI, MARIA, and OPAL reactors.[45] Also, the fabrication of this fuel is well understood, and will be more cost effective than the U-7Mo dispersion fuel. The drawback is that the uranium density is much lower at 4.8 gU/cm^3.[46] While LEU fuel at this density was sufficient for the previous reactors, JHR is designed to generate a higher neutron flux (exceeding $5x10^{14}$ n.cm^{-2}.s^{-1} in the core and in the reflector) and in the absence of higher density will need to use a higher enrichment level to obtain more fissile U-235. The reactor will initially operate with 27% HEU fuel in order to have increased flexibility to conduct experiments under high radiation damage environments. As CEA stated: "Therefore, as a temporary solution, the RJH can start with a U_3Si_2 fuel using an enrichment slightly above 20% depending on the power demanded."[47]

According to NNSA officials, their CEA counterparts have pledged to convert to use high-density LEU dispersion fuel when such fuel is available.[48] In September 2013, France's CEA and Russia's Rosatom reached a deal for Rosatom to export HEU for the JHR reactor. Russia does not seem to adhere to the same requirement as the United States in terms of requiring a

[44] Private discussions with NNSA personnel.
[45] HFR Petten is a reactor in the Netherlands, SAFARI in South Africa, Maria in Poland and Opal is in Australia.
[46] Van den Berghe, Sven, and P. Lemoine. "Review of 15 years of high-density low-enriched UMo dispersion fuel development for research reactors in Europe." Nuclear Engineering and Technology 46, no. 2 (2014): 125-146.
[47] Machine translated from the French. The official English version is: "Consequently, as a back-up solution, the JHR may start with U3Si2 fuel using a slightly higher enrichment depending on the requested power".
[48] The designers of the JHR in Cadarache France had planned to use high density U-Mo LEU fuel but they now intend to start with 27% HEU instead. In fact, CEA (Commissariat a l'energie atomique) has recently secured an agreement with the Russian State Company Rosatom to procure HEU for the reactor. http://fissilematerials.org/blog/2013/09/russia_to_supply_heu_fuel.html

commitment for those countries to convert. Since the reactor is not yet in use it is difficult to estimate the expected HEU use.

In any case, JHR is an outlier in fuel conversion efforts. The reactor's operators participate in fuel qualification efforts and coordinate with NNSA but the two do not have a close relationship other than fuel qualification. The EU funded LEU-FOREvER consortium is currently conducting the HiPROSIT full fuel plate tests in the BR-2 reactor to "extend the use of U_3Si_2 dispersion fuel to higher powers" that are required for reactors like JHR.[49]

The Belgian Reactor 2 (BR-2) Reactor: U-7Mo Dispersal Fuel or U_3Si_2 Dispersal Fuel

The BR2 reactor is a high-performance reactor operated since 1961 by the Belgian nuclear research center known as SCK.CEN.[50] The reactor uses about 29 kg of 93% enriched fuel per year, and the operator has agreed to convert to LEU as soon as an appropriate LEU fuel is qualified. The reactor is used for isotope production and for NTD silicon doping as well as accelerated testing of materials including fuel. These activities generate commercial revenue used to supplement the cost of the reactor. The reactor is run at 60-70 MW but is designed for 100 MW. The BR-2 is one of a handful of major global producers for medical isotopes and produces 20-25% of the world's supply of such isotopes.[51] Medical isotope targets for Mo-99 production as well as fuel for the BR-2 have been fabricated at Areva/CERCA in France but the HEU for the fuel has come from the United States. The NNSA has transferred 93.35% enriched HEU in the form of "broken metal pieces" from Y-12 HEU storage to France.

The NNSA obtained a license in 2006 to export 85.5 kg of 93.4% enriched HEU to France for BR-2 fuel production. At the time NRC complied with NNSA's request because it was expected that the reactor would be converted to LEU fuel within three years noting: "It is estimated that this quantity of material will sustain BR2 operation from about 2007 through 2010, at which time the Belgian Nuclear Research Center expects to convert the reactor to high-density low enriched uranium (LEU) fuel that has been qualified for that facility." Unfortunately, the reactor was not converted as expected so NNSA requested another transfer of 93.5 kg HEU in 2010. The license was issued in June 2010 and the HEU transferred in October 2010 to Areva/CERCA although BR2 had not been converted.

[49] https://hal-cea.archives-ouvertes.fr/cea-02339322/file/201800000014.pdf
[50] http://www.research9-reactors.eu/en/Br2/br2.html
[51] https://www.nrc.gov/docs/ML1624/ML16244A813.pdf

In 2014 another request from NNSA was made—to export 144 kg of 93.4% enriched HEU to Areva/CERCA. However, soon thereafter this request was withdrawn and SCK.CEN "announced a tender to choose a new supplier, which was completed in January 2016." The company chosen to manufacture the fuel was the U.S. company Babcock & Wilcox negating the need to export HEU to France. However, Babcock and Wilcox subsequently applied to the NRC to export the same amount of HEU (but in fuel) directly to the BR-2 in a series of shipments over 10 years, despite opposition from some nonproliferation advocates. The estimated HEU use annually is about 39 kg,[52] more than enough for a nuclear weapon.

The High Flux Reactor (Réactor à Haut Flux [RHF]): U3Si2 Dispersal Fuel

The RHF reactor is based in Grenoble and is managed and operated by the Institut Laue-Langevin (ILL). It first reached criticality in 1972. The reactor is used for basic science: scientists there produce more than 600 publications per year, making ILL the "most scientifically productive neutron facility of any kind." The reactor has more than 40 instruments to support its activities plus two guide halls.[53]

In 1998, operators committed to convert the RHF to LEU, however, "by that time France began receiving HEU from Russia, so the conversion efforts were suspended." In the late 1990's there were several exports of HEU from Russia to France for the RHF reactor in Grenoble and the ORPHEE research reactor in Saclay.[54]

The NNSA Y-12 National Security Complex applied for an NRC license in 2010 to transfer 160 kg of 93.4% enriched HEU to France to fabricate fuel for the RHF in two shipments of 80 kg. ILL predicts that under the current fuel inventory they can operate until "2020-2025."[55] According to the 2016 NAS report the RHF can meet its operating envelope and safety margin requirements with currently developed U_3Si_2 dispersion fuels.

[52] fissilematerials.org/library/rr15.pdf
[53] National Academies of Sciences, Engineering, and Medicine. *Reducing the use of highly enriched uranium in civilian research reactors.* National Academies Press, 2016, page 48.
[54] U.S. to supply HEU for the High Flux Reactor in France, IPFM Blog, MARCH 11, 2010. fissilematerials.org/blog/2010/03/us_to_supply_heu_for_the_.html
[55] U.S. to supply HEU for the High Flux Reactor in France, IPFM Blog, MARCH 11, 2010. fissilematerials.org/blog/2010/03/us_to_supply_heu_for_the_.html

US Reactors

The United States has six high performance research reactors (USHPRR) that all use HEU fuel cores. There are plans to convert all of them when appropriate fuel is available. In collaboration with European colleagues, NNSA has successfully developed a high-density U-10Mo alloy LEU fuel that can be used to convert all USHPRR's. In 2009, researchers completed feasibility studies demonstrating the ability to convert all of the U.S. reactors. Since then, NNSA has achieved key fuel design milestones en route to qualifying the fuel: "seven irradiation campaigns consisting of 14 large size plates and over 60 mini plates with U-10Mo fuel with a zirconium interlayer" were performed.[56] A significant milestone was NNSA's submission of a report on U-Mo Monolithic fuel to the U.S. Nuclear Regulatory Commission (NRC) in 2017. According to NNSA, the report contains data about the performance of the new fuel and how it holds up under a variety of conditions.[57] As described below, each of the USHPRR's are unique in their design and utilization, and each reactor's fuel elements needed to be redesigned to use LEU fuel. Between 2014 and 2017, operators at three reactors also submitted to the NRC Preliminary Safety Analysis Reports (PSAR's) required for conversion. These reactors, described below, are the National Institute of Standards Reactor (NBSR), the University of Missouri Research Reactor (MURR), and the Massachusetts Institute of Technology Reactor (MITR). The other three reactors, the Advanced Test Reactor (ATR), and its associated critical assembly (ATRC), and the High Flux Isotope Reactor (HFIR) have all completed preliminary designs for U-10Mo fuel. However, unlike the other reactors, the HFIR reactor has selected a "silicide (U_3Si_2) fuel design with a fuel meat density of 4.8 gU/cm^2." The HFIR fuel choice will "require additional fuel qualification due to the complex fuel design containing boron and since HFIR exceeds existing silicide qualification limits."[58]

The geometry of the U-10Mo fuel includes an LEU foil with a thickness between 0.06-0.08 mm., a thin 0.025 mm zirconium diffusion barrier, and an aluminum cladding. This configuration uses equipment not in regular use at the BWXT. The process consists of "multiple complex thermomechanical processes, including casting, homogenization, hot-roll bonding of the Zr diffusion barrier, cold rolling, intermediate annealing, and hot isostatic pressing."[59] BWXT and Y-12 struggled

[56] E. H. Wilson et al, U.S. HIGH PERFORMANCE RESEARCH REACTOR PRELIMINARY DESIGN MILESTONE FOR CONVERSION TO LOW ENRICHED URANIUM FUEL, RRFM 2019. https://www.euronuclear.org/download/rrfm-2019-part-3/?wpdmdl=4557&refresh=60197569b98b51612281193

[57] https://www.energy.gov/nnsa/articles/nnsa-reaches-milestone-developing-new-nuclear-fuel-us-high-performance-research

[58] E. H. Wilson et al, U.S. HIGH PERFORMANCE RESEARCH REACTOR PRELIMINARY DESIGN MILESTONE FOR CONVERSION TO LOW ENRICHED URANIUM FUEL, RRFM 2019. https://www.euronuclear.org/download/rrfm-2019-part-3/?wpdmdl=4557&refresh=60197569b98b51612281193

[59] Wight, Jared M., Vineet V. Joshi, and Curt A. Lavender. USHPRR FUEL FABRICATION PILLAR:

for several years to achieve consistency in fabrication but have finally managed to do so, consistently producing foils for miniplates and full-size foils, not just small size foils for experiments. To improve efficiency, NNSA is planning to invest in more cold and hot mills. BWXT now has the capability to fabricate fuel for all NRC licensed reactors. However, experiments still need to be conducted to understand the limits on bounding performance specifications (performance limits for safe use of the fuel).

LEU fuel for the MIT reactor is set to be qualified in 2024 and the reactor converted to using the new fuel a few years after that. Other conversions are then expected to follow. Details on the status of the five high performance research reactors are below.

The successful conversion of reactors requires meeting a series of milestones, which operators seem well on the way to achieving. The series of steps and milestones are listed in Table 2 and take decades to achieve.

Table 3: List of steps required and milestones for reactor conversion.[60]

Step	Milestone
Feasibility designs	Preliminary U-10Mo designs
Preliminary designs	Preliminary submission of safety reports to NRC
Preliminary safety analysis review	Fabrication demonstrations
Preliminary regulator reviews	U-10Mo fuel qualification report
Reactor specific irradiations and flow testing	Demonstration element irradiations
Final conversion safety analysis reports	Final conversions
Regulator safety analysis review and LEU licensing	

The MIT Research Reactor (MITR)

The MIT research reactor is a light-water cooled and moderated, heavy-water reflected, nuclear reactor that has been in operation since 1958.[61] The thermal neutron flux available for use is $6x10^{13}$ neutrons/cm^{2}-s and the fast neutron flux exceeds 10^{14} neutrons/cm^{2}-s. The reactor serves as an important tool for

FABRICATION STATUS, PROCESS OPTIMIZATIONS, AND FUTURE PLANS. No. PNNL-SA-132285. Pacific Northwest National Lab(PNNL), Richland, WA (United States), 2018.

60 Wilson, E. H., J. I. Cole, C. Lavender, K. Dunn, and M. Cercy. “Preliminary Fuel Development and Reactor Design Milestones for LEU Conversion of US High Performance Research Reactors.” In Proc. Int. Conf. Nuclear Security, pp. 10-14.

61 https://nrl.mit.edu/reactor

material analysis, in-core experiments, advanced fuel studies etc. There are several experimental facilities available both within the core and using neutrons delivered through beam ports, including medical irradiation rooms. The reactor was upgraded from 5 MW to 6 MW in 2010 and is now known as the MITR-II reactor. The reactor is primarily supported by the DOE Office of Nuclear Energy "through the Nuclear Science User Facilities (NSUF) research grants, small business innovation research, and national laboratories."[62]

High Flux Isotope Reactor (HFIR)

The HFIR reactor is currently the "highest flux reactor-based source of neutrons for research in the United States" and "provides one of the highest steady-state neutron fluxes of any reactor in the world."[63] Like the MITR reactor it is used by hundreds of researchers for a variety of purposes spanning from condensed matter experiments to medical uses. It has four independent experimental beam facilities. It was originally constructed to produce isotopes such as californium-252 (Cf-252) which can only be produced via multiple neutron captures.[64] The reactor is entirely supported and regulated by DOE and is operated and based at Oak Ridge National Laboratory in Tennessee.

The University of Missouri Research Reactor (MURR)

The principal focus of the MURR reactor is medical isotope production. It partners with the company Northstar to produce non-uranium-based Mo-99 by irradiating Mo-98 targets.[65] The reactor also produces the radioisotope lutetium-177 (Lu-177) which can be used to treat certain types of tumors as recently approved by the U.S. Food and Drug Administration. The MURR is supported by the DOE Office of Nuclear Energy and commercial ventures.

[62] National Academies of Sciences, Engineering, and Medicine. Reducing the use of highly enriched uranium in civilian research reactors. National Academies Press, 2016.
[63] https://neutrons.ornl.gov/hfir
[64] The isotope berkelium-249 is bombarded, which forms berkelium-250. This element then quickly decays and forms Cf-250. The isotope then captures several neutrons to eventually become Cf-252.
[65] https://www.world-nuclear-news.org/Articles/Four-US-companies-chosen-for-Mo-99-production-fund

The Advanced Test Reactor (ATR) plus critical assembly

The ATR reactor, based at the Idaho National Laboratory, is the “only U.S. research reactor capable of providing large-volume, high-flux neutron irradiation in a prototype environment.” Most of the work conducted by the ATR reactor is classified and used to support the US. Navy’s nuclear propulsion development work, while 10% is focused on other applications. The ATR reactor is the principal reactor for producing medical grade cobalt-60 (Co-60) for cancer therapy around the world. It operates at 250 MW, similar to the power of a Small Modular Reactor used for electric power generation. Another unique characteristic of this reactor is the configuration of the fuel (known as ‘serpentine’ core) which allows a variety of flux levels to be tested simultaneously.

The Neutron Beam Split-Core Reactor (NBSR)

The NBSR is a reactor based at the National Institute for Standards and Technology Center for Neutron Research in Gaithersburg, Maryland. The reactor has 30 dedicated instruments and researchers working there produce more than 300 scientific publications per year. The reactor has several cold neutron sources—powerful tools whose increased wavelength improves spatial resolution in neutron scattering experiments.[66] NIST is in the process of constructing a liquid deuterium neutron trap that cools neutrons to -252 Celsius -- ideal for neutron scattering measurements. The source is “partially funded by the NNSA Material Management and Minimization Program to compensate for the 10% reduction in neutron flux that will result from LEU conversion.”[67]

Japan

The Kyoto University Critical Assemblies (KUCA) conversion studies with Argonne National Laboratories of the United States have been continuing since 2008. They are now progressing in an international partnership including South Korea, France and the United States. The U7Mo powder atomized by KAERI is being formed into aluminum-clad coupons by Framatome-CERCA in a close collaboration with Japan, the US, CERCA, and with KAERI. For the second LEU fuel used in KUCA, Kyoto University has identified a solution using fuel fabricated by Framatome CERCA. Fuel for

[66] Boualem Hammouda, PROBING NANOSCALE STRUCTURES USING SANS, ncnr.nist.gov/staff/hammouda/distance_learning/chapter_4.pdf

[67] Birgeneau, Robert, Sue Clark, Pengcheng Dai, Thomas Epps, Karsten Heeger, David Hoogerheide, Marc Kastner et al. “The Scientific Justification for a US Domestic High-Performance Reactor-Based Research Facility.” (2020).

the KUCA reactor is being prepared for qualification and manufacturing. Things are "progressing very well," according to NNSA officialx. An update was given at the 2021 RERTR conference where it was reported that the expected performance of the cores are "compatible with the capabilities of the existing cores." Furthermore, no 'modification of reactor components (for example the control rods, core support system etc) appear to be required.' It is also expected that the spectrum will be harder than the HEU core which will improve performance in simulating light water reactors. When conversion takes place, it will be the first critical assembly to be fully converted.[68]

[68] H. Unesaki et al, KUCA support of Japan's Nuclear Engineering and Science, RERTR Virtual Conferenc, April 20, 2021.

Russia

Conversion

A 2017 report, The Use of Highly Enriched Uranium as Fuel in Russia, published by the International Panel on Fissile Materials, calculated that there were 58 nuclear-powered ships fueled with HEU and 58 facilities in Russia that used HEU for research, isotope production, power generation or as naval reactors prototypes by April 2017.[69] The same report indicated that the equivalent of roughly 3.3 tons of 90 % HEU was used in Russia annually. There are no more up-to-date, publicly available reports available on the country's civilian HEU stocks: Russia like the majority of States possessing HEU, does not provide public information on them.[70] However, our examination of multiple open-source documents helped identify changes in research facilities using HEU since 2017, still leaving Russia with 43 HEU-fueled facilities, by far the largest such nuclear fleet in the world and more than half the world total (See Table 4 below).

Table 4: Changes in Russian HEU fueled research facilities since 2017

Facility	**Type**	**Status in the 2017 report (page)**	**Later status**
SF-1	Critical assembly	Being decommissioned (119)	(As of 13 March 2018) decommissioned[71]
SF-7	Critical assembly	Being decommissioned (119)	(As of 13 March 2018) decommissioned[72]
UG	Critical assembly	Being decommissioned (120)	(As of 12 March 2018) permanent shutdown[73]
IRT-MEPhI	Steady state research reactor	Suspended for reconstruction (120)	(As of 13 March 2018) extended shutdown[74]

69 http://fissilematerials.org/library/rr16.pdf, pp. 2-3.
70 Only a handful of states provide public information on their HEU holdings for example through IAEA INFCIRC 549 (plutonium guidelines) and INFCIRC 912 (see above).
71 https://nucleus.iaea.org/rrdb/RR/HeaderInfo.aspx?RId=650
72 https://nucleus.iaea.org/rrdb/RR/HeaderInfo.aspx?RId=653
73 https://nucleus.iaea.org/rrdb/RR/HeaderInfo.aspx?RId=647
74 https://nucleus.iaea.org/rrdb/RR/HeaderInfo.aspx?RId=300

Astra	Critical assembly	Operation suspended for modernization (119)	(As of 13 March 2018) operational[75]
FS-2	Subcritical assembly	Restarted in October 2015 (121)	(As of 29 November 2016) permanent shutdown[76] But licence renewed on 19 December 2016 until 19 December 2021[77]
PIK	Steady state research reactor	In operation at 100 W (121)	Reached its first criticality on 28 February 2021, power start-up on 8 Feb 2021[78]
BR-10	Fast reactor	Shut down in 2002. Being decommissioned (122)	(As of 9 March 2018) permanent shutdown[79]
FS-1M	Critical assembly	In operation (122)	(As of 12 March 2018) decommissioned[80]
ST-1120	Critical assembly	Shut down in 1996 (124)	(As of 13 March 2018) decommissioned[81]
FKBN-2M	Critical assembly	Under modernization (126)	(As of 18 May 2018) operational[82]

The full list of Russian research facilities using HEU, compiled on the basis of publicly available nformation, may be found in Annex I to the present report.

The 2016 US National Academies research reactor study pointed to the large number of Russian reactors as well as some of their particular risks and conversion challenges: “Many are critical and subcritical -- assemblies which can pose particular risk because the fuel is lightly irradiated and there can be large amounts of fuel stored on site…Converting most of the remaining Russian research reactors is possible with existing or soon-to-be-qualified

[75] https://nucleus.iaea.org/rrdb/RR/HeaderInfo.aspx?RId=655
[76] https://nucleus.iaea.org/rrdb/RR/HeaderInfo.aspx?RId=725
[77] https://www.nikiet.ru/images/obes/9702.pdf
[78] https://tass.com/science/1253791
[79] https://nucleus.iaea.org/rrdb/RR/HeaderInfo.aspx?RId=302
[80] https://nucleus.iaea.org/rrdb/RR/HeaderInfo.aspx?RId=634
[81] https://nucleus.iaea.org/rrdb/RR/HeaderInfo.aspx?RId=678
[82] https://nucleus.iaea.org/rrdb/RR/HeaderInfo.aspx?RId=734

LEU fuel. However, conversion of its domestic research reactors is not a high national priority for Russia."[83]

Indeed, our review of open-source information and our interviews with Russian and non-Russian experts on the country's domestic activities in the HEU minimization domain indicated that the topic was no longer on the agenda of policymakers. For example, Russia-US feasibility studies on the conversion of six Russian HEU-fueled research reactors[84] have yielded little action. The studies began after a 2010 agreement[85] between Russia's State Atomic Energy Corporation ROSATOM and the US Department of Energy. The Russian side declared that conversions would occur if they were "economically and technically justified."[86] The studies found that conversion was feasible for all six reactors, and one of the six reactors (the Argus reactor) was converted to LEU fuel.[87] The IRT-M reactor at the Moscow Engineering Physics Institute (MEPhI) was planned to be converted, as well.[88] Yet a decade later, the remaining five research reactors are still using HEU, without any plans for conversion. [89]

The experts interviewed provided diverging views on the reasons why Russia has put reactor conversion efforts on hold. One of the interviewees mentioned that it was a political decision. Another expert, however, noted that he was not aware of any official decision in ROSATOM to abandon the conversion plans. In his view, reactor operators had framed the issue as a technical one: believing that conversion of certain types of reactors, for example, high-neutron flux reactors, would entail loss of their efficiency and limiting the range of experiments that can be carried out, a belief that does not appear to be borne out by empirical evidence.[90]

---

[83]National Academies of Sciences, Engineering, and Medicine 2016. Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors. Washington, DC: The National Academies Press, p. 5. https://doi.org/10.17226/2181

[84] IR-8, OR, and ARGUS reactors at the Kurchatov Institute; IRT-M at the Moscow Engineering Physics Institute; IRT-T at the Tomsk Polytechnic University; and MIR.M1 at the Scientific Research Institute of Atomic Reactors. http://nas-sites.org/dels/files/2015/05/Day2_02_ROGLANS_NASRussiaConvertApr2015.pdf

[85]Implementing Agreement between the Russian State Corporation for Atomic Energy (Rosatom) and the Department of Energy (DOE) Regarding Cooperation in Concluding Feasibility Studies of the Conversion of Russian Research Reactors," https://www.energy.gov/articles/us-russian-federation-sign-joint-statement-reactor-conversion.

[86] World Nuclear Association - World Nuclear News (world-nuclear-news.org). https://www.world-nuclear-news.org/RS-Russian_research_reactors_may_convert_to_LEU_fuel-0912104.html

[87] http://nas-sites.org/dels/files/2015/05/Day2_02_ROGLANS_NASRussiaConvertApr2015.pdf

[88] http://fissilematerials.org/library/rr16.pdf, p. 60.

[89] For example, the IRT-T research reactor in Tomsk is expected to operate until 2035. Source: https://news.tpu.ru/news/2020/09/28/36768/?mode=print

[90] We feel it is important to note that while reactor operators often mention that one of their concerns about conversion is a "flux penalty," but that is most often not the case. See Appendix for a description of a survey carried out of 33 research reactor operators who have converted their reactors about their experiences.

One expert also shared his views on the possibility of conversion of certain research reactor types. He indicated that technical features of IRT and WWR (also known as VVR) reactors allow the use of fuel with various enrichment levels and contended that modifying these reactors would entail needless work and costs. Critical assemblies BFS-1 and BFS-2 at the Institute of Physics and Power Engineering (Obninsk) are designed to use U-235 enriched both to 36% and 90%, and some experts contend they need both types of fuel to obtain a precise balance of fissile material, particularly for modelling fast neutron reactor systems and thus are not worth converting. Whether this is in fact technically necessary or rather a point of pride or prestige is open to question. According to a 2008 article, some research and educational establishments in Russia considered it a matter of prestige to possess HEU-fueled reactors, even when those reactors were in shutdown.[91] Reasons cited included the possibility of "returning to the field of nuclear materials research in the future" and the fact that such reactors could obtain greater funding for staff, isotope production, materials testing, and nuclear material protection, control, and accounting.

While the conversion process has stalled on the political side, there is still some work being done on the technical side. Several interviewees emphasized that there are hopes of eventual development and certification of high-density LEU fuel to be used in high performance reactors. Efforts are underway in Russia in this regard.[92] Furthermore, the process of HEU minimization happens de facto as some reactors using HEU are put in an extended shutdown (e.g., IRT-M reactor in MEPhI) or retired, to be replaced by new reactors using non-HEU fuel. The latter is the case of the BOR-60 reactor, which uses both HEU and LEU fuel (depending on research needs). It is planned to be replaced by the Multi-Purpose Fast Reactor (MBIR), which is currently under construction as part of a plan to create a center of excellence[93] and will use mixed-oxide fuel containing uranium and plutonium (which of course comes with its own nuclear security concerns).[94] Lastly, Russian nuclear security expert Dmitry Kovchegin noted during a December 2020 presentation that the Kurchatov Institute had taken organizational control of a substantial part of nuclear R&D facilities in Russia, and now controls the majority of research reactors that use HEU fuel.[95] He later wrote that "Other than international pressure to reduce the use of HEU, the only valid chance for downsizing use and decreasing stocks of HEU in Russia is the drive for economic efficiency. Ongoing consolidation of the nuclear

---

[91] Elena K. Sokova (2008) PHASING OUT CIVILIAN HEU IN RUSSIA, *The Nonproliferation Review,* 15:2, 209-236. https://doi.org/10.1080/10736700802117288.
[92] https://www.atomic-energy.ru/news/2018/09/26/89124
[93] Multi-Purpose Fast Reactor (MBIR). http://www.niiar.ru/eng/node/4508
[94] State funding for Russia's MBIR reactor - Nuclear Engineering International (neimagazine.com), December 18, 2019. https://www.neimagazine.com/news/newsstate-funding-for-russias-mbir-reactor-7561163
[95] National Research Center «Kurchatov Institute» (nrcki.ru). http://eng.nrcki.ru/

research complex in Russia can reduce the number of smaller research facilities using HEU."[96]

When asked about the possibility of resuming Russia-US cooperation in the field of conversion, including track 1.5 or track 2 formats, three of the interviewed experts expressed diverging views. According to one expert, Russian interest in dialogue on conversion is non-existent and ROSATOM was always skeptical in that regard. He did suggest, however, that one possible way forward to engage Russia in cooperation with the US could lie in testing and certifying new Russian LEU high-density fuel that could be exported to foreign research reactors.[97]

Another expert underlined that informal Russia-US discussions were still taking place. As an example, he mentioned regularly held international conferences on research reactors, such as the international conference on "Research Reactors: Addressing Challenges and Opportunities to Ensure Effectiveness and Sustainability", held in Buenos Aires, Argentina, on 25–29 November 2019. He added, however, that the US Government unilaterally stopped cooperation with Russia in that field since 2015-16 and even certain private US companies were dissuaded from establishing ties with Russia. Additionally, Russian counterparts also experienced problems with obtaining US visas. The expert also noted Russia's negative experience with the bilateral Plutonium Management and Disposition Agreement, where the US unilaterally changed the plutonium disposition method without Russian agreement. Similarly, the third expert mentioned that Russia is open for cooperation in the nuclear sphere and stated that "the ball is in US court."

HEU Production

Russia also continues to produce HEU both for internal use at research reactors and for export. For example, in 2011, ROSATOM announced plans to boost the capacity of an enrichment plant in Zelenogorsk by approximately 30% and to use it as its main enrichment plant with 90% of the new centrifuges installed there.[98] Much of this effort was done to produce fuel for domestic research and fast neutron reactors.[99] As for exports, in 2015, the Zelenogorsk plant produced HEU for the German FRM-II research reactor[100]

[96]Dmitri Kovchegin, International Nuclear Security Forum Country Update: Russian Nuclear Security, Henry L. Stimson Center, May 12, 2021. https://www.stimson.org/2021/international-nuclear-security-forum-country-update-russian-nuclear-security/
[97] Similar incentives for Russian HEU conversion were proposed in a 2014 paper by one of the authors and two Russian colleagues: Anton Khlopkov and Miles Pomper, with Valeriya Chekina, *Ending HEU Use in Medical Isotope Production,* Nuclear Threat Initiative, 2014. https://www.nti.org/analysis/articles/ending-heu-use-medical-isotope-production
[98] https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-fuel-cycle.aspx
[99] Annual Report of Electrochemical Plant, 2012, p. 13. http://www.ecp.ru/sites/default/files/download/go_ecp_12.pdf
[100] http://www.tvel2015.ru/static/pdf/tvel_report_2015_ru.pdf P. 79.

and, in July 2019, ROSATOM delivered a batch of HEU fuel for China's CEFR fast neutron reactor.[101]

When asked why Russia continues to produce more HEU while still having considerable HEU stocks, one expert provided several possible explanations. First, it may be considered easier to produce fresh HEU rather than retrieve it from the stocks as Russia has amassed significant and underutilized enrichment capacity. Secondly, HEU from the weapons program, which comprises most of the stocks, was said to have a chemical composition unsuitable for the needs of foreign customers that opt for freshly enriched HEU. Third, the HEU stocks are kept as a sort of a fuel bank for potential periods of global enriched uranium scarcity. In that event, Russia can down blend down its HEU and use it as LEU reactor fuel.

One future opportunity to diminish Russia's civilian HEU stocks may come from a new Rosatom-funded research project to use HEU to help make new fuel out of the spent fuel of light water reactors. According to Kovchegin, "This technology received Rosatom investment in 2020, and production facilities will be built on the site of the Siberian Chemical Combine."[102]

Removal of Russian-origin HEU Fuel from Research Reactors or Critical Assemblies Outside Russia

During the reporting period, Russia continued to implement the Russian Research Reactor Fuel Return Program aimed at returning from third countries HEU fuel for research reactors supplied by Russia.[103] For more information, please see the following section on Kazakhstan.

Belarus

It is difficult to assess the current stockpile of HEU in Belarus since the country does not report this information voluntarily. However, 2014 estimates compiled by CNS showed 80-280 kg of HEU, with approximately 40 kg of it enriched to 90% or higher levels.[104] The 2020 estimates of the International Panel on Fissile Materials provide a far larger range of 100-1000 kg of HEU.[105]

In a joint Belarus-US statement made on the sidelines of the 2011 Astana summit of the OSCE, Belarus committed to eliminate its HEU stockpile by

---

101 https://www.world-nuclear-news.org/Articles/TVEL-delivers-fuel-for-China%E2%80%99s-experimental-fast-r
102 Kovchegin, International Nuclear Security Forum Country Update: Russia Nuclear Security.
103 http://russiannuclearsecurity.com/july-august2020issue
104 https://media.nti.org/documents/heu_who_has_what.pdf
105 Highly enriched uranium - International Panel on Fissile Materials. http://fissilematerials.org/materials/heu.html

2012.[106] Prior to that declaration, Belarus and Russia agreed on a fuel swap: HEU from Belarus would be sent to Russia in exchange for LEU fuel.[107] In 2011, after several batches of HEU had been successfully transported to Russia, Belarus halted the HEU-removal process in retaliation for EU and US sanctions.[108] More recently, discussions between Washington and Minsk appeared to be making progress before the current domestic political crisis in Belarus. While they put a temporary halt to talks, US officials are "very hopeful" the efforts can be revived even as they caution that "baby steps" are still needed to move forward. U.S. officials had looked to the anticipated return of the US ambassador to Minsk later this year to provide an opportunity for moving forward, but the recent forced landing of a civilian airliner in Belarus may have scotched those plans yet again.

One Russian expert also mentioned that there is still an ongoing project on developing high-density LEU fuel for the Hyacinth critical assembly facility, involving the US and Russia (as a fuel producer). Moreover, the two critical facilities (Hyacinth and Crystal) and one subcritical assembly (Yalina-B) already have the ability to run with either HEU or LEU for fuel and prefer using LEU in the fast critical assembly but have not yet parted with their HEU. The country is also planning to build a new storage facility for non-irradiated nuclear material, Yavor-1.[109]

South Africa

The South African government has taken the position that "[d]etails regarding the uranium stockpiles are classified and therefore cannot be disclosed publicly."[110] The material is under IAEA safeguards, and the amount is known to the IAEA based on South Africa's initial declaration to the agency in 1991. However, all safeguards-related information is confidential.[111] Therefore, only estimates are available. One study, for example, estimated that South Africa possessed 700-750 kg of HEU at the end of 2014.[112]

106 Belarus Agrees to Give Up HEU Stockpile, Arms Control Association. https://2009-2017.state.gov/r/pa/prs/ps/2010/12/152168.htm

107 Article 2, Соглашение между Правительством Российской Федерации и Правительством Республики Белоруссия о сотрудничестве по ввозу в Российскую Федерацию облученного и свежего высокообогащенного ядерного топлива исследовательских реакторов и поставке в Республику … Международное соглашение от 08 октября 2010 года (cntd.ru).

108 PomperPAB514.pdf (stanleycenter.org)

109 2020 report of the World Bank Group, p. 23. https://openknowledge.worldbank.org/bitstream/handle/10986/34336/Strengthening-Hydromet-and-Early-Warning-Services-in-Belarus-A-Road-Map.pdf?sequence=1&isAllowed=y

110 PMG, "Minister of Energy: Reply to Question 1807 (NW2199E)," August 2012, https://pmg.org.za/question_reply/342/

111 Back to Valindaba: SA's plan to enrich uranium - The Mail & Guardian (mg.co.za) https://mg.co.za/article/2013-10-11-00-back-to-valindaba-sas-plan-to-enrich-uranium/ in PomperPAB514.pdf https://stanleycenter.org/publications/PomperPAB514.pdf (stanleycenter.org), p. 4.

112 David Albright, Highly Enriched Uranium Inventories in South Africa Status as of end of

South African Nuclear Energy Corporation's NTP Radioisotopes SOC Ltd, in cooperation with the US Department of Energy's National Nuclear Security Administration, completed conversion of its molybdenum-99 medical isotope production process from HEU to LEU in 2008,[113] and NTP has used only LEU targets since August 2017.[114] Hence the last issue related to the HEU minimization effort in South Africa is its current HEU stock (both fresh and in spent fuel). After 6.5 kg of US-origin, South African HEU spent fuel was shipped back to the US in 2011,[115] South Africa's HEU stock is said to only contain material produced indigenously.

As President Obama led the Nuclear Security Summits from 2016, he sought to persuade South African president Jacob Zuma to part with the material, as noted by Jo-Ansie Van Wyk of the South African Institute of International Affairs.

> In a letter dated 16 August 2011 US President Barack Obama nudged his South African counterpart, saying that it would be 'a highlight' of the 2012 Nuclear Security Summit in Seoul 'if you [Zuma] were to announce that South Africa will blend down' all its HEU to produce LEU for medical isotope production. In a subsequent letter in 2013, Obama again tried to persuade Zuma to surrender the country's HEU stockpile, stating it was his 'strong hope' that Zuma would be able to announce at the Nuclear Security Summit in The Hague in 2014 'that South Africa will dispose of all its remaining spent HEU fuel'. In return, Obama offered to provide South Africa with 350kg LEU, promote the South African medical isotope industry, and dispatch a team of experts to South Africa. Obama also stated that Zuma's decision should 'build on and enhance South Africa's legacy of nuclear leadership'.[116]

2014, 2015, p. 8, http://large.stanford.edu/courses/2019/ph241/greene1/docs/isis-2015.pdf#:~:text=South%20Africa%20produced%20highly%20enriched%20uranium%20%28HEU%29%20for,early%201990%2C%20was%20designed%20to%20make%20weapon-grade%20uranium.

[113] NNSA collaborates with South African firm on ground-breaking conversion to low-enriched uranium-based molybdenum-99 production, Department of Energy. https://www.energy.gov/nnsa/articles/nnsa-collaborates-south-african-firm-groundbreaking-conversion-low-enriched-uranium

[114] Current Molybdenum-99 Supply, Opportunities and Approaches for Supplying Molybdenum-99 and Associated Medical Isotopes to Global Markets: Proceedings of a Symposium, The National Academies Press (nap.edu). https://www.nap.edu/read/24909/chapter/5#15

[115] World Nuclear Association, World Nuclear News (world-nuclear-news.org). https://www.world-nuclear-news.org/RS-US_origin_HEU_returned_from_South_Africa-1908114.html

[116] Jo-Ansie Van Wyk, Special Report: Nuclear Energy in South Africa, South African Institute of International Affairs, February 2021, p.35.

But Zuma could not be budged. According to knowledgeable sources, US and South African officials came tantalizingly close to an agreement to remove the spent South African HEU but Zuma blocked it.

Interviews and an analysis of open-source information point to three major reasons that South Africa retains an HEU stockpile. First, as mentioned by one interviewed expert, South Africa considers that the HEU might be useful for socioeconomic development in the future in view of advances in technology and science. Secondly, the possession of the HEU remains a symbol of the country's international status and sovereignty in nuclear matters and insistence that non-nuclear-weapon-states' rights under the NPT not be curbed.[117] The last, but most probably the most important argument for HEU possession is its continuous use as a bargaining chip for global nuclear risk reduction through nuclear weapons disarmament.[118] For example, while acknowledging the need to explore technically and economically feasible ways to minimize HEU, South Africa nevertheless underlined that the reduction should happen for military as well as civilian HEU stocks.[119]

Additionally, one expert mentioned yet another issue that hampers meaningful discussion on the HEU minimization between South Africa and Western countries: it is a perception among the latter that South Africa as a developing country is not capable of protecting its HEU. The country indeed witnessed a break in to the Pelindaba facility by two teams of armed intruders in 2007, who eventually spent nearly an hour inside the secured perimeter and then disappeared. Not all of the important details of the investigation of the incident were released nor had South Africa accepted previous US offers to remove the HEU at Pelindaba or to help improve security at the facility. The interviewed expert nevertheless mentioned that South Africa had eventually introduced considerable improvements to the physical protection arrangements at Pelindaba with US assistance. The expert further mentioned in this context that many other states also had experienced nuclear security incidents, for example, the 2012 incident at the US Y-12 HEU storage facility.

---

[117] "The Major Prize": Apartheid South Africa's Accession to the Treaty on the Non-Proliferation of Nuclear Weapons, *The Nonproliferation Review,* Vol 26, No 5-6, 1988–91. https://www.tandfonline.com/doi/full/10.1080/10736700.2019.1696543

[118] Statement by President of the Republic of South Africa HE Jacob Zuma, at the Leaders' Working Dinner hosted by President of the Republic of Korea HE Lee Myung-bak at the Nuclear Security Summit, Seoul, Republic of Korea, the Presidency of the Republic of South Africa, 26 March 2012. http://www.thepresidency.gov.za/speeches/statement-president-republic-south-africa-he-jacob-zuma%2C-leaders%E2%80%99-working-dinner-hosted

[119] cn-278-south-africa.pdf (iaea.org), p. 2. https://www.iaea.org/sites/default/files/20/02/cn-278-south-africa.pdf

Near-term progress on minimizing South Africa's fresh HEU fuel stockpile is unlikely. Yet, under the Ramaphosa administration, prospects do appear brighter for perhaps removing some spent fuel out of domestically produced HEU than they did under the previous government.

Miniature Neutron Source Reactors (MNSRs)

Miniature Neutron Source Reactors (MNSRs) are compact light water

30 kW research reactors, which are used for neutron activation analysis, research, and training. They have small cores containing less than 1 kg of HEU (90 % U-235). Developed by the China Institute of Atomic Energy (CIAE), these reactors are modeled after the Canadian SLOWPOKE and US TRIGA reactors.[120]

CIAE has designed and manufactured nine MNSRs since the mid-1980s: four in China and five overseas, one each in Pakistan (1989), Iran (1994), Ghana (1995), Syria (1996), and Nigeria (2004). Two MNSRs in Shanghai and Shandong in China have been shut down,[121] but the other two reactors in China remain operational. According to the IAEA Research Reactor Database, MNSRs in Iran, Pakistan, and Syria are operational as well.

In 2009 during an industry meeting in Beijing, the United States and China agreed to address reactors with smaller, but still proliferation-sensitive, quantities of HEU, and specifically, the MNSRs that China had supplied to Iran, Pakistan, Syria, Ghana, and Nigeria. Over the next year, the two sides worked out the details of a deal in which the United States would pay $1.7 million and build a Zero Power Test Facility (ZPTF) in China. The facility would be used to test new LEU MNSR cores to ensure that they met existing reactor performance and safety standards.[122] In return, China would shoulder the cost of converting the MNSRs that it had supplied.[123] The first conversion of an MNSR was completed in March 2016 in China.[124] Since then, two more MNSRs including one in Ghana and Nigeria have been successfully converted and nearly 2 kg of HEU spent fuel (90% U-235) were safely repatriated to China.
The MNSRs' unique technical features – they operate at low power and have relatively small fuel rods (4 mm in diameter and 250 mm long[125]) – make them especially "attractive candidates for conversion,"

---

[120] Zhou Youngmao, "A Safe Private Nuclear Tool: The Miniature Neutrone Source Reactor," IAEA Collection, 1985, pp. 253-259. https://inis.iaea.org/collection/NCLCollectionStore/_Public/20/012/20012796.pdf?r=1&r=1
[121] "Analyses Supporting Conversion of Research Reactors from High Enriched Uranium Fuel to Low Enriched Uranium Fuel," IAEA-TECDOC-1844. https://www-pub.iaea.org/MTCD/Publications/PDF/TE1844-Web.pdf
[122] S. A. Jonah, Y. A. Ahmed, *Conversion of Nigeria MNSR and Lessons Learned from Operator's Perspective,* International Meeting on Reduced Enrichment for Research and Test Reactors, Edinburgh, Scotland, 4 November 2018, www.rertr.anl.gov, http://pub.iaea.org.
[123] Alan J. Kuperman, ed., *Nuclear Terrorism and Global Security: The Challenge of Phasing Out Highly Enriched Uranium* (Abingdon, UK: Routledge, 2013), 106.
[124] *National Progress Report: China, Nuclear Security Summit,* March 31, 2016. http://www.nss2016.org/document-center-docs/2016/3/31/national-progress-report-china-1
[125] Zhou Youngmao, "A Safe Private Nuclear Tool: The Miniature Neutron Source Reactor," IAEA Collection, 1985, pp. 253-259. https://inis.iaea.org/collection/NCLCollectionStore/_Public/20/012/20012796.pdf?r=1&r=1

explain engineers from the Argonne National laboratory.[126] According to the IAEA, with the conversions of Ghana and Nigeria MNSRs, all 11 operational reactors in Africa are now running on LEU fuel.[127] Still, conversion is a laborious and technically challenging process. Individual MNSRs are configured slightly differently from the generic HEU MNSR core including varying the number of fuel rods.[128] Therefore, each reactor conversion requires a customized approach. To ensure the same level of power output and the same reactor's performance, a new LEU core needs to be created.

The remaining portion of this section provides a summary of the successful reactor conversions in China, Ghana, and Nigeria. It continues with a description of the current state of MNSR conversions in Iran, Pakistan, Syria, and China and probes into reasons for delays.[129]

Successful MNSR Conversions

MNSR IAE (Beijing, China)

The reactor known as MNSR IAE is operated by the China Institute of Atomic Energy in Beijing. It is used for neutron activation analysis, radioisotope productions, and irradiation testing.[130] It was converted by a partnership of the China Atomic Energy Authority (CAEA) and the U.S. Department of Energy. The HEU fuel was unloaded in 2015. and in March 2016, the LEU fuel (U-235 enriched at 12.5%) was loaded in the reactor's core. The MNSR IAE reached its full capacity on March 26, 2016.[131]

GHARR-1 (Accra, Ghana)

The MNSR reactor designated as GHARR-1 is operated by the Ghana Atomic Energy Commission's National Nuclear Research Institute. Conversion of the GHARR-1 reactor to LEU was completed in July

---

[126] https://www.ans.org/news/article-211/the-ongoing-effort-to-convert-the-worlds-research-reactors/

[127] Pyotr Chakrov, Thomas Hanlon, "Nigeria Converts its Research Reactor from HEU to LEU," IAEA, December 20, 2018. https://www.iaea.org/newscenter/news/nigeria-converts-its-research-reactor-from-heu-to-leu-fuel

[128] "Analyses Supporting Conversion of Research Reactors from High Enriched Uranium Fuel to Low Enriched Uranium Fuel," IAEA-TECDOC-1844. https://www-pub.iaea.org/MTCD/Publications/PDF/TE1844-Web.pdf

[129] Miles Pomper, Ferenc Dalnoki-Veress, "The Little Known Success Story of U.S – China Nuclear Security Cooperation," Nuclear Threat Initiative, June 10, 2020. https://www.nti.org/analysis/articles/little-known-success-story-us-china-nuclear-security-cooperation/

[130] IAEA Research Reactor Database, https://nucleus.iaea.org/RRDB/RR/ExpmtlFacility.aspx?RId=56

[131] "One of China's MNSR reactors converted to LEU," FMWG Blog, March 29, 2016. http://fissilematerials.org/blog/2016/03/one_of_chinas_mnsr_reacto.html

2017 through multilateral cooperation between Ghana, the United States, China, and the IAEA. The reactor's spent HEU fuel, about 1 kg, was returned to China in August 2017.

NISRR-1 (Zaria, Kaduna Region, Nigeria)

The 2018 conversion of the Center for Energy Research and Training NIRR-1 research reactor marked a milestone as it became the final operational reactor in Africa to switch to LEU fuel. The reactor reached its full capacity using LEU fuel in late November 2018.

About 1 kg of spent HEU fuel was repatriated to China at the end of 2018. The conversion of the NIRR-1, initiated by the Nigerian Atomic Energy Commission, with financial and implementation support from China, Norway, the United Kingdom, the United States, and the IAEA.

Remaining MNSR Conversions

Various IAEA reports and studies determined that MNSR conversions to LEU both within and outside China, are feasible without any compromises to the reactor's performance and its safety. The issue of the HEU spent fuel unloaded from the converted MNSR reactors has been addressed as well. China signed agreements with IAEA and Ghana and Nigeria to accept their MNSRs spent HEU fuel and it has already received LEU from these two countries when their reactors have been converted. China has also concluded an agreement with Syria and indicated to the IAEA its readiness to take spent fuel from MNSRs in Iran and Pakistan.[132]

Furthermore, successful conversions of MNSRs in Ghana and Nigeria serve as evidence that foreign-built reactors can be converted with support from a supplier. However, there are still three MNSRs outside of China (Iran, Pakistan, and Syria) and one in China which have yet to convert to LEU fuel. The progress of these four MNSR conversions is best described as "very close but yet so far away."[133]

ENTC MNSR (Isfahan, Iran)

ENTC MNSR is operated by the Esfahan Nuclear Technology Centre. According to the IAEA Research Reactor Database,[134] the ENTC

[132] Medical Isotope Production without Highly Enriched Uranium, National Academy of Sciences, 2009. https://www.ncbi.nlm.nih.gov/books/NBK215149/pdf/Bookshelf_NBK215149.pdf
[133] CNS interview with a US government official.
[134] IAEA Research Reactor Database. https://nucleus.iaea.org/RRDB/RR/ExpmtlFacility.aspx?RId=218

MNSR is used for neutron activation analysis. Iran participated in all technical meetings, but it is not clear if Iran has a specific conversion program in place. Oddly, the reactor's conversion was not included in the 2015 Joint Comprehensive Plan of Action (JCPOA) between the P5+1 and the Iranians as its conversion was apparently not regarded as a priority. Renewed negotiations involving the United States and Iran, however, could open the door to such a conversion, perhaps as a good-will gesture. A potential arrangement would be for the United States to fund the conversion but not be involved at the technical level.[135] Technical assistance will most likely be provided by China which has expressed its readiness to help with conversion and accept spent fuel from the Iranian MNSR. Russia could assist with the transport of fuel using Czech SKODA casks.[136]

PARR-2 (Islamabad, Pakistan)

PARR-2 MNSR is operated by the Pakistan Institute of Nuclear Science & Technology. Like most MNSRs, the PARR-2 is used for neutron activation analysis. According to Pakistani officials, their country remains committed to HEU minimization in principle, while keeping in view some economic, technical, and political constraints. As for financial support, it is believed that there are international donors ready to assist. China has also confirmed its intent to receive the reactor's spent fuel. According to some sources, the lack of a clear political commitment by Pakistan to move forward—via a letter to the IAEA-- is the main reason for a delay.

SRR-1 (Damascus, Syria)

SRR-1 MNSR is operated by the Atomic Energy Commission of Syria (AECS) and is used mainly for neutron activation analysis.[137] According to some sources, China signed an agreement to accept HEU fuel from the SRR-1 reactor, but the agreement was concluded before the Syrian civil war broke out in 2011.

One expert mentioned that the IAEA was in contact with Syria concerning technical questions related to the conversion of the MNSR and the removal of the HEU fuel. According to the MNSR operators, the reactor is in a secure area. There is, however, no information yet on whether any donor has committed to sponsoring the project.[138]

135 CNS interview with a US government official.
136 CNS interview with a US government official.
137 IAEA Research Reactor Database, https://nucleus.iaea.org/RRDB/RR/ExpmtlFacility.aspx?RId=218
138 CNS interview with a US government official.

Another source mentioned that Syria has asked the IAEA for support twice. Although Russia might seem a potential sponsor of the conversion, the same source expressed doubt that Russia would provide such funding.

MNSR-SZ (Shenzhen, China)

MNSR-SZ is operated by the Institute of Joint Nuclear Techniques. The reactor is used for neutron activation analysis, training and teaching. While generally committed to covert the MNSR-SZ, reactor operators say that a lack of funding lies behind the delay.

Kazakhstan

For the past five years, Kazakhstan has been steadily working with international partners, including the United States, the IAEA, and Russia, through bilateral and multilateral initiatives to eliminate HEU from its Soviet-built research reactors. These efforts include the completion of the conversion of the VVR-K (or WWR-K) reactor at the Institute of Nuclear Physics (INPh) in Alatau and ongoing conversions of two research reactors IGR and IVG.1M at the National Nuclear Center of the Republic of Kazakhstan in Kurchatov (Eastern Kazakhstan), as well as downblending or removing fresh and spent HEU fuel.

VVR-K Reactor Conversion: Summary

The conversion of the VVR-K reactor at the INPh, took about a decade and was successfully completed in April of 2016. The reactor has been operating on LEU fuel since September 2016.

The complete elimination of all HEU from the VVR-K reactor, including the downblending of 49.3 kilograms of fresh HEU fuel and the removal of 158.3 kilograms of irradiated HEU, was reported by the U.S. NNSA in September 2020.

IGR and IVG.1 M Reactors Conversion Process Update

IGR Reactor Updates

Conversion efforts at the two research reactors at the National Nuclear Center located on the territory of the former Semipalatinsk Nuclear Test Site ("Test Field" site) in Eastern Kazakhstan have been going on for more than a decade. At the last Nuclear Security Summit in 2016, Kazakhstan reaffirmed its pledge to convert the IVG1.M and IGR reactors to LEU and remove remaining fresh and spent HEU fuel from the research centers."

The IGR reactor at the National Nuclear Center (NNC) in Kazakhstan is one of the oldest research reactors in the world, having begun operation in 1961. The facility is a pulse reactor with a homogeneous uranium-graphite core. According to an IAEA conference paper prepared jointly by US and Kazakhstani authors, HEU fuel from the first reactor core was never used in a reactor and has been stored at the reactor site.

In 2019, the government of Kazakhstan made a decision to downblend fresh HEU graphite fuel from the IGR reactor at the Ulba Metallurgical Plant (UMP) in Oskemen (formerly, Ust-Kamenogorsk), Kazakhstan.   This was done in a collaboration between Kazakhstan's Ministry of Energy and the U.S. NNSA. Because the HEU in the reactor was mixed with graphite, thousands of blocks of graphite needed to be packaged, placed in casks, and removed in unusual ways. According to NNSA officials, it took 25 trucks to remove the graphite blocks mixed with 2.9 kg of unirradiated HEU. In September 2020, NNSA reported the successful downblending of the unirradiated HEU.

IVG. 1M Reactor Updates

The water-cooled reactor IVG.1M, also at the former Semipalatinsk Test Site ("Baikai-1" site), represents an upgrade of the gas-cooled reactor IVG.1 "which was used for testing fuel assemblies and the cores of high temperature gas-cooled reactors, including reactors of nuclear spacecraft propulsion and nuclear engineering power systems. IVG.1 reactor fuel was exported to Russia during its modernization into IVG.1M." Like the VVR-K reactor, the IVG.1M is also cooled with water, but it has a completely different design, requiring a different conversion process.

In 2017, two experimental channels with LEU fuel, manufactured by the Russia's Federal State Unitary Enterprise Scientific-Research Institute "LUCH," were loaded into the IVG.1M reactor for testing. The next year, the National Nuclear Center of Kazakhstan in Kurchatov reported that the test was successful.

The United States and Kazakhstan signed a Joint Statement during the 2020 IAEA General Conference, committing to convert the IVG.1M research reactor from the use of HEU to LEU fuel in 2021. This will also lead to the future removal of HEU spent fuel from the site. In discussions with the CNS research team, NNSA officials commended the progress made by their Kazakhstani counterparts despite the pandemic, noting that they had completed fuel qualification, and had provided a safety analysis and startup plan to Kazakhstani regulators.

In February 2021, another important milestone was reached in the IVG.1M conversion process. When LEU fuel produced by LUCH was delivered to the reactor site. It is expected that the fuel will be uploaded to the reactor this year and that the reactor with its new core will become operational in 2023.

Despite considerable progress with research reactors conversions, Kazakhstan remains the only country in the Central Asian region with significant HEU holdings. It is estimated that about 10 tons of HEU is contained in the spent fuel from the decommissioned BN-350 fast reactor. While the spent fuel is stored at a secure long-term storage facility at the Semipalatinsk Test Site and is placed under the IAEA safeguards, Kazakhstan has not declared specific plans for permanent storage or a disposition pathway.

Mo-99

Efforts to minimize civilian HEU use recently reached a crucial milestone last May when the Belgian firm IRE began processing irradiated LEU targets to produce the vital medical isotope molybdenum-99, the last major Mo-99 producer to do so. Mo-99 is the dominant diagnostic tracer and is used in about 30 million medical procedures each year for diagnoses of a broad range of diseases in many parts of the human body, including cancer, heart disease and neurological disorders such as dementia. It is produced in reactors by irradiating uranium “target” plates and then separating out the Mo-99. The separated Mo-99 with a half-life of less than a week is then placed in generators where it decays into the even shorter-lived technetium-99m (Tc-99m).

Historically, producers used HEU in the uranium targets as it was cheaper and produced less waste. Production is heavily concentrated: there are only a handful each of major production reactors and major Mo-99 processing facilities worldwide and NNSA has worked with those facilities to convert. As with reactors, the United States has pushed for the conversion of targets to LEU, primarily by leveraging Congressional restrictions over HEU exports to foreign reactors under the Schumer Amendment.

IRE’s full conversion to LEU is ongoing and could take as long as another year to complete as its wide network of foreign customers must first obtain domestic regulatory approvals for the new LEU-based Mo-99 and resulting Tc-99M. Still, one U.S. official said that: “Finally with IRE there is a finality there. They have made finalizing this conversion a true priority and they are communicating it to their customers.” Indeed, in March, the operators of the Dutch High Flux Reactor announced that it was solely irradiating LEU targets for Mo-99 processing (at IRE and Curium). Relevant U.S. officials are closely monitoring the transition and are confident that the United States has shipped its last HEU to Europe for this purpose.

Getting to this point required overcoming a series of technical, economic, and political challenges. An essential role was placed by the OECD/NEA High Level Group on Security of Supply of Medical Radioisotopes (HLG-MR), which brought together key representatives from supplier and consumer countries after a 2009 supply crisis threatened patient care worldwide. The HLG-MR concluded in a series of reports that previous Mo-99 supply shortages had occurred because older HEU-fueled reactors had their capital costs effectively subsidized, making it difficult for new LEU-based competitors to enter the market and compete successfully. When those older reactors then faltered there was no backup supply. The HLG-MR stressed the importance of ending the subsidies (“full cost recovery”), a goal still only partly achieved.

A breakthrough occurred when European host countries for several major isotope producers in Europe committed at the 2012 Nuclear Security Summit to push their firms to convert to LEU, assuming regulatory approvals.

The U.S. 2013 American Medical Isotopes Production Act put additional pressure on foreign reactors to convert. The law used financial incentives to boost support for LEU-based Mo-99, provided funding for the development of domestic non-HEU Mo-99 production, and called for an end to US HEU exports for isotope production in seven years, with additional delays of up to six years permitted if the Secretary of Energy certified that "there is insufficient global supply of molybdenum-99 produced without the use of highly enriched uranium available to satisfy the domestic United States market; and…that the export of United States-origin highly enriched uranium for the purposes of medical isotope production is the most effective temporary means to increase the supply of molybdenum-99 to the domestic United States market."

Acting Secretary of Energy Dan Brouillette made such a certification on January 2, 2020, waiving the export ban for up to two years, because of IRE's failure to convert by that point. However, he promised that "DOE will conduct periodic reviews of the domestic U.S. and global Mo-99 market and will work toward a certification to Congress, regarding the sufficiency of supply as soon as the statutory conditions are satisfied." It appears that IRE's conversion efforts have advanced enough that another delay should not be required.

Outer Space Missions

There has been a resurgence in interest in using fission reactors for deep space missions. The first application is to provide energy for an outpost on the Moon or Mars, a so-called Surface Power Reactor. Reliable electricity is a necessity for any remote outpost and typical alternatives such as Radioisotope Thermoelectric Generators (RTGs) that rely on the heat produced from the natural decay of radioactive isotopes without a fission chain reaction are not practical for producing the needed 50 kilowatts of power.

The U.S. National Aeronautics and Space Administration (NASA) tested a solution to this problem with the KRUSTY reactor experiment in 2018. This experiment used a fission reactor to produce heat. That heat was then converted into mechanical energy in a Stirling Engine, which uses the heat to drive a piston up and down. Finally, the mechanical energy could then be converted to electricity to power the outpost.

Unfortunately, the KRUSTY reactor requires 30 kg of weapons- grade HEU in its core to produce just 1 kilowatt of electricity. That would be enough HEU for as many as half a dozen nuclear weapons yet it would produce just enough power to heat an electric kettle or operate a two-slice toaster. NASA claims that a 10kW version would require 50 kg of weapons-grade uranium. It claimed that an LEU version of this reactor would be much heavier—a key consideration on space missions where every effort is made to minimize. A recent study has found that an LEU based reactor would be about twice as heavy.

In December 2020, the Trump Administration issued a directive to restrict (but not ban) HEU use in future space missions. The new regulation states that HEU use “should be limited to applications for which the mission would not be viable with other nuclear fuels or non-nuclear power sources.” This high bar all but bans use of HEU for future power missions and is a step in the right direction.

Another application of fission reactor could be to aid rocket propulsion. The heat provided by the reactor is used to “burn hydrogen in the rocket engines.” The thrust is comparable to regular liquid-fuel rockets, but efficiency may be much higher. The advantage of this application is that astronauts could return to Earth for up to three months of their scheduled seven-month journey if anything goes wrong on the way. If conventional rockets are utilized, this window is only a few days. A solicitation is underway requesting designs for a reactor that can supply “hundreds of megawatts of thermal energy to run the engine.” Four companies (BWX Technologies, General Atomics, X Energy, and Ultra Safe Nuclear Corp.) are expected to bid on the grant, and all are planning to use LEU.

Appendix 1

Applications for Exports of WG HEU from USA to Europe and other countries. The purpose / end use are taken directly from the license.

XSNM (License #)	Applicant Date	Date Granted	Mass U (kg)	ENR (%)	Temp Dest	Final Dest	Purpose/End Use
XSNM3545	7/14/2008	11/4/2008	16.33	93.31%	Canada	Canada	To fabricate targets for irradiation in the National Research Universal (NRU) Reactor to produce medical isotopes
XSNM3600	7/21/2009	9/17/2009	0.04658	93.16%		United Kingdom	Fabricate neutron detector
XSNM3622	2/2/2010	6/11/2010	87.3	93.37%	France	Belgium	To fabricate fuel elements in France for use as fuel in the BR–2 reactor in Belgium. The BR–2 reactor is used for research and the production of medical isotopes
XSNM3622/01	5/30/2012	9/6/2012	5.8	93.55%	France	Belgium	Fuel and target fabrication as an intermediate use. Reactor fuel and medical isotope production as a final use for the following reactors: BR-2, HFR (Petten), OSIRIS (Gif-sur-Yvette), LVR-15 (Czech Republic)
XSNM3623	12/28/2009	7/1/2011	7	93.33%	Canada	Canada	To fabricate targets for irradiation in the National Research Universal (NRU) Reactor to produce medical isotopes
XSNM3633	10/21/2011	3/16/2012	174	93.35%	France	France	To fabricate fuel elements in France for use as fuel in the Institut Laue—Langevin (ILL) High Flux Reactor (HFR) in France
XSNM3701	9/23/2011	12/27/2011	0.293	93.91%	South Korea	South Korea	45 fission chambers each containing between 3.9 and 8.1 gram 94% enriched uranium, for neutron flux monitoring.
XSNM3702	10/5/2011	7/13/2012	0.1342	93.19%	China	China	Up tp 24 intermediate range core detectors each containing up to 6 grams of U-235 for work on AP1000 NPP's.
XSNM3708	12/22/2011	7/2/2012	9.3	93.00%	Netherlands	Netherlands	To manufacture HEU targets in France for irradiation in research

							reactors for fabrication of molybdenum99 (Mo-99) medical isotopes in the Nuclear Research and Consultancy Group in the Netherlands. Amend to: 1) add Maria Reactor in Poland and Covidien Isotope Production Facility in the Netherlands to "Intermediate Foreign Consignees(s)"; and 2) extend the expiration date from March 31, 2013 to December 31, 2013.
XSNM3726	8/1/2012	10/24/2012	7	93.33%	Canada	Canada	For the export of high-enriched uranium in the form of broken metal to the Atomic Energy of Canada Limited (AECL) laboratories in Canada, for the production of targets for the use in medical isotopes production.
XSNM3729/01	10/18/2013	1/3/2014	12.615	93.44%	France	Belgium	Target Fabrication for Mo-99 Medical Isotopes for the following end use reactors: BR-2, HFR (Petten), OSIRIS, LVR-15.
XSNM3730/1	9/12/2013	11/20/2013	17.1	92.93%	France	Netherlands	Target fabrication for Mo-99 production using the following reactors: HFR, BR-2, Maria Reactor (Poland), and Mallinckrodt Mo Production Facility (Petten).
XSNM3745	5/21/2013	8/27/2013	7	93.33%	Canada	Canada	Targets for Mo-99
XSNM3751	4/7/2014	10/7/2014	0.056	93.33%	South Korea	South Korea	15 fission chambers each containing 3.9 of enriched uranium in the ex-core neutron flux monitoring systems at Shin-Kori 4 and Shin-Wolsong 1 or 2
XSNM3752	4/28/2014	8/18/2014	7	93.33%	Canada	Canada	Targets for medical isotope production.
XSNM3753	5/16/2014	6/10/2014	0.2999	99.97%	Belgium	Belgium	Reference material for safeguards. Large-Size Dried (LSD) spikes for nuclear safeguards measurements for quality control of measurements.
XSNM3754	6/23/2014	7/8/2016	0.188	94.00%	UAE	UAE	51 fission chambers with each containing 3.9 grams each of enriched uranium used in neutron flux monitoring systems at 4 reactors. For Barakah NPP.

XSNM3755	9/22/2014	1/26/2015	3.73	93.25%	Netherlands	Netherlands	Targets for medical isotope production in reactors: HFR. BR-2 and Maria (Poland)
XSNM3756	9/22/2014	2/24/2015	7.28	93.33%	France	Belgium	Targets for medical isotope production in reactors: HFR. BR-3 and Maria (Poland)
XSNM3757	12/23/2014	10/5/2016	121	93.08%	France	France	Targets for medical isotope production in reactors: BR-2, HFR, Osiris, LVR-15 (Czech), Maria (Poland).
XSNM3758	12/23/2014		134.2	93.19%	France	Belgium	Fuel fabrication for BR-2 Reactor Fuel Reload
XSNM3761	3/11/2015	6/23/2015	7.56	93.33%	Canada	Canada	Targets for medical isotope production.
XSNM3771	6/3/2016	3/3/2017	134.208	93.20%		Belgium	BR-2 fuel reload
XSNM3772	6/10/2016	1/6/2017	0.6	100.00%	Japan	Japan	Intermediate use is dissolution of metals for lab use for calibration and quality control of safeguards measurements.
XSNM3774	6/28/2016	6/19/2017	0.13	92.20%		China	Thirty-six (36) fission chambers containing 3.9 grams each of enriched uranium used in neutron flux monitoring systems at two reactors. The total includes eight quadruple fission chamber power range and intermediate range detector assemblies (four for each reactor) and one spare detector assembly.
XSNM3775	1/30/2017	6/14/2017	0.293	93.91%		South Korea	54 fission chambers each containing between 3.9 and 8 grams of enriched uranium used in neutron flux monitoring systems at 6 reactors. Reactors: Hanul-2, Hanbit 1 and 2, Shin-Hanul 1 and 2.
XSNM3776	7/21/2016	8/3/2017	3.45	93.24%	France	Belgium	Target fabrication/ irradiation for Mo-99 medical isotope production for reactors: BR-2, HFR, LVR-15, Maria (Poland).
XSNM3777	9/27/2016	4/20/2017	2.8	93.33%	Canada	Canada	Target irradiation/Mo-99 production.
XSNM3778	2/7/2017	3/16/2017	0.02256	94.00%		Slovenia	Six fission chambers containing 3.9 g each of enriched uranium used in

							neutron flux monitoring systems at two reactors. The total includes two dual fission chamber source range and intermediate range detector assemblies and one spare detector assembly. Reactor: Krško Nuclear Power Plant (Slovenia).
XSNM3788	12/12/2017	3/20/2018	1.35	93.10%	France	Belgium	Target fabrication/ irradiation for Mo-99 medical isotope production for reactors: BR-2, LVR-15, Maria (Poland).
XSNM3790	2/20/2017	10/18/2018	0.1	100.00%		Japan	Tracer applied to safeguards analyses.
XSNM3792	3/8/2018	5/31/2018	.02	91.74%		United Kingdom	Fabrication of neutron detector for the company Centronic Limited in Croyden, Surrey, UK.
XSNM3794	3/12/2018	4/23/2018	4.913	93.16%	France	Belgium	Target fabrication/ irradiation for Mo-99 medical isotope production for reactors: BR-2, HFR, LVR-15, Maria (Poland).
XSNM3795	8/17/2018	10/12/2018	4.63	93.16%	France	Belgium	Target fabrication/ Irradiation for Mo-99 medical isotope production for reactors: BR-2, HFR, LVR-15, Maria (Poland).
XSNM3805	10/15/2018	7/18/2019	0.044	91.67%		UAE	Twelve fission chamber containing 3.9 grams each of 0.048 KG of enriched 94% 0.044 KG of U-235 enriched uranium used in neutron flux monitoring systems as uranium spares at four. Total includes four reactors (4) triple fission chamber detector assemblies. For the Barakah Unite 1,2,3,4.
XSNM3806	10/15/2018	3/11/2019	0.143	94.08%		South Korea	Thirty-nine (39) fission chambers each containing between 3.9 to 8.0 grams of enriched uranium used in neutron flux monitoring systems at twelve reactors. For use at Kori 3&4, Shin Kori 1-4, Hanul, 1 & 2, Hanbit 1 &2 and Shin Hanul 1-2.
XSNM3810	8/5/2019	4/13/2020	4.455	93.36%	France	Belgium	Target fabrication/ irradiation for Mo-99 medical isotope production for reactors: BR-2, HFR, LVR-15, Maria (Poland).

XSNM3813	5/11/2020	6/18/2020	0.3	94.00%		Belgium	The JRC-Geel uses the NBL Program Office uranium metal by dissolving them, and splitting them into much smaller samples containing the uranium, and adding plutonium which they source from France (not US plutonium). These small samples containing milligram quantities of uranium and plutonium, called LSD spikes, are Certified Reference Materials (CRM's). The LSD spike CRM's are purchased, mostly by Japan, to be used for material accountability determinations, overseen by the IAEA. These materials and the LSD spikes that are created are required to meet international safeguards agreements. The NBL PO and the IAEA participate in JRC-Geel reviews of these materials, to ensure their suitability for use in meeting accountability and measurement requirements.
XSNM3816	7/20/2020	8/20/2020	0.044	93.62%	United Kingdom	United Kingdom	To provide secure storage to meet both UK and IAEA safeguards and security requirements due to the quantity of material to be held and to provide chemical form conversion to uranyl nitrate hexahydrate to allow Ultra to use it inside neutron flux sensors. Springfields Fuel is the destination.
XSNM3819	9/18/2020		121.16	93.20%	France	France	To provide secure storage to meet both UK and IAEA safeguards and security requirements due to the quantity of material to be held and to provide chemical form conversion to uranyl nitrate hexahydrate to allow Ultra to use it inside neutron flux sensors. Springfields Fuel is the destination.

Appendix 2

Research Reactor Conversions and Shutdowns

Cumulative	Country	Facility	Conversion/ Shutdown Date	Notes
1	Mexico	TRIGA Mark III	1968	Partial (1968); Full (2012)
2	Taiwan	THOR	1978	Full
3	France	Osiris	1979	Full
4	Austria	TRIGA II	1980	Partial (Sep-80); Full (Nov-12)
5	Brazil	IEA-R1	1981	Full
6	United States	Michigan, Ford	1982	Converted then shut down
7	Austria	ASTRA	1983	Converted then shut down
8	United States	RTR - Critical Assembly, RPI	1987	Full
9	United States	RTR - GE, Worcester Poly Research Reactor	1987	Full
10	Argentina	RA-3	1987	Full
11	Philippines	PRR-1	1987	Converted then shut down
12	United States	RTR - Research Reactor	1988	Full
13	Denmark	DR-3	1988	Converted then shut down
14	Sweden	R2	1990	Converted then shut down
15	Switzerland	Paul Scherrer Institute (PSI)	1990	Converted then shut down
16	United States	RTR - UTR-10	1991	Converted then shut down
17	Germany	FRG-1	1991	Full
18	Pakistan	PARR-1	1991	Full
19	United States	Manhattan College Zero Power Reactor	1992	Converted then shut down

20	United States	MSTR Building	1992	Full
21	Romania	SSR Pitesti	1992	Full
22	Canada	NRU - National	1992	Full
23	United States	Rhode Island Nuclear Science Center	1993	Full
24	Iran	TRR (NRCRR)	1993	Full
25	Japan	JMTR	1993	Full
26	Turkey	TR-2	1994	Full
27	United States	Georgia Institute of Technology Research Reactor	1997	Converted then shutdown
28	United States	University of Virginia Reactor	1997	Converted then shutdown
29	Canada	Slowpoke - 2 Montreal		Full
30	Colombia	IAN-R1	1997	Full
31	Germany	BER-II	1997	Full
32	Japan	JRR-4	1998	Full
33	Netherlands	HOR	1998	Full
34	Slovenia	TRIGA-MARK II	1999	Full
35	Canada	MNR McMaster	1999	Full
36	Chile	RECH-1	1999	Full
37	Greece	GRR-1	1999	Full
38	Sweden	R2-0	1999	Converted then shut down
39	United States	RTR - University of Massachusetts Lowell RTR	2000	Full
40	Australia	HIFAR	2004	Full
41	Germany	ZLFR	2005	Shut down prior to conversion
42	Czech Republic	VR-1 Vrabec (Sparrow)	2005	Full

43	Netherlands	HFR	2005	Full
44	Libya	Critical Facility	2006	Full
45	Germany	FRJ-2	2006	Shut down prior to conversion
46	United States	RTR - Texas A&M Nuclear Science Center Reactor	2006	Full
47	United States	RTR - University of Florida Training Reactor	2006	Full
48	Libya	IRT-1	2006	Full
49	France	Ulysse	2007	Shut down prior to conversion
50	China	MNSR-SH	2007	Shut down prior to conversion
51	China	HFETR	2007	Full
52	China	HFETR CA	2007	Full
53	Portugal	RPI	2007	Full
54	United States	RTR - Electrical Engineering Building	2007	Full
55	Vietnam	Dalat Research Reactor	2007	Partial (September-07); Full (November-11)
56	Uzbekistan	VVR-SM	2008	Full
57	United States	Zero Power Research Reactor	2008	Shut down prior to conversion
58	South Africa	SAFARI-1 Building 1800	2008	Full
59	Argentina	RA-6	2008	Full
60	United States	RTR - Nuclear Radiation Center	2008	Full
61	United States	RTR – OSU	2008	Full
62	Ukraine	WWR-M	2008	Full
63	United States	General Atomics Research Reactor	2008	Shut down prior to conversion
64	Bulgaria	IRT-2000	2009	Shut down prior to conversion

65	United States	RTR - University of Wisconsin - Research Reactor	2009	Full
66	Hungary	BRR	2009	Full
67	United States	NRAD - Neutron Radiography Reactor	2009	Full
68	Russia	PhS-4 (FS-4)	2010	Shut down prior to conversion
69	Russia	PhS-5 (FS-5)	2010	Full
70	Russia	STRELA	2010	Shut down prior to conversion
71	Japan	KUR	2010	Full
72	Chile	RECH-2 Research	2010	Shut down prior to conversion
73	China	MNSR-SD	2010	Shut down prior to conversion
74	Czech Republic	REZ 10 MW Research Reactor	2011	Full
75	Russia	BR-10	2011	Shut down prior to conversion
76	Russia	MR reactor	2011	Shut down prior to conversion
77	Canada	Slowpoke Halifax	2011	Shut down prior to conversion
78	Japan	YAYOI	2012	Shut down prior to conversion
79	Japan	MITI Standard Pile	2012	Shut down prior to conversion
80	Russia	TIBR	2012	Shut down prior to conversion
81	Netherlands	LFR	2012	Shut down prior to conversion
82	Poland	Maria Research Reactor	2012	Full
83	Kazakhstan	VVR-K CA	2012	Full
84	Russia	RF-GS	2012	Shut down prior to conversion
85	India	Apsara	2013	Shutdown prior to conversion
86	China	MJTR	2013	Full
87	United Kingdom	Consort	2013	Shutdown prior to conversion
88	Indonesia	PT BATAN Teknologi Mo-99 Production Facility	2013	Converted to LEU targets

89	Russia	ARGUS	2014	Full
90	Russia	ROSSIYA	2014	Shutdown prior to conversion
91	Russia	ROSSIYA	2014	Shutdown prior to conversion
92	Uzbekistan	Foton	2014	Shutdown prior to conversion
93	Switzerland	AGN-211P	2015	Shutdown prior to conversion
94	Jamaica	Slowpoke UWI CNS	2015	Full
95	Kazakhstan	VVR-K	2016	Full
96	China	CIAE Beijing MNSR-IAE	2016	Full
97	Japan	Fast Critical Assembly	2016	Shutdown prior to restart as an accelerator
98	South Africa	Pelindaba - Building 1701 - Isotope Production Facility	2016	Converted to LEU targets
99	Canada	Alberta SLOWPOKE	2017	Shutdown prior to conversion
100	Ghana	GHARR-1 MNSR	2017	Full
101	Netherlands	Covidien Petten Mo-99 Production Facility	2017	Converted to LEU targets
102	Canada	AECL Mo-99 Production Facility	2018	Shutdown prior to conversion
103	Nigeria	NIRR-1 MNSR	2018	Full
104	France	Minerve	2019	Shutdown
105	France	Masurca	2019	Shutdown
106	Canada	Saskatchewan	2019	Shutdown
107	France	ORPHEE	2021	Shutdown
107	**in 42 countries and Taiwan**		**1978 through Feb, 2021**	

Appendix 3

Research Reactors to be Converted

Reactor	Country	Name	TYPE	STATUS
1	Belarus	Hyacinth/Giacint	Critical Assembly	Operational according to the 2016 NAC study
2	Belarus	Crystal/Kristal	Critical Assembly	Extended shutdown (RRDB: 24 January 2018)
3	Belarus	Yalina-B	Subcritical Assembly	Operational (18 December 2016) according to RRDB but also according to the 2016 NAC study
4	Belgium	BR2	HPRR-EU	Dispersion fuel performance for BR2 and JHR has still not been proven. In this case, a combination of fuel meat interaction with surrounding matrix and recrystallization at high burnups are believed to limit the fuel performance.
5	Belgium	VENUS	Fast Critical Assembly	Operational (RRDB: 16 March 2018)
6	China	MNSR-SZ	MNSR	Operational (RRDB: 5 November 2020)
7	China	Zero	Power Fast Fast Critical Assembly	Extended shutdown (RRDB: 24 January 2018)
8	China	CEFR	Prototype Fast Power	Operational (RRDB: 5 November 2020)
9	DPRK	IRT-DPRK	Steady State	Operational in 2016 NAC study
10	DPRK	IRT-DPRK CA	Critical Assembly	Operational in 2016 NAC study
11	France	RHF	HPRR-EU	Dispersion fuel performance for BR2 and JHR has still not been proven. In this case, a combination of fuel meat interaction with surrounding matrix and recrystallization at high burnups are believed to limit the fuel performance.
12	France	Phenix	Critical Assembly	Under decommissioning (RRDB: 29 May 2017)
13	France	Jules Horowitz Reactor (JHR) Steady State (under construction)	HPRR-EU	Committed to convert once fuel is available
14	Germany	FRM-II	HPRR-EU	Committed to convert once fuel is available
15	Iran	ENTC	MNSR	Operational (RRDB: 6 May 2019)

16	Israel	IRR-1	Steady State	Reactor is to be phased out by 2018 according to 2013 post in RRDB
17	Italy	TAPIRO	Steady State	Operational (RRDB: 5 November 2020)
18	Japan	FCA	Fast Critical Assembly	Permanent shutdown (RRDB: 10 March 2011) however operation according to the 2016 NAC
19	Japan	KUCA	Critical Assembly	Kyoto University Critical Assemblies (KUCA): U7Mo powder atomized by KAERI of Korea is being formed into aluminum-clad coupons by Framatome CERCA of France in a close collaboration of Japan, the US, CERCA, and KAERI. For the second LEU fuel used in KUCA, Kyoto University has identified a solution using fuel fabricated by Framatome CERCA.
20	Japan	UTR-Kinki	Steady State	Operational (RRDB: 1 May 2018)
21	Kazakhstan	IVG-1M	Steady State	Operational according to the 20156 NAC study. United States and Kazakhstan signed a Joint Statement during the 2020 IAEA General Conference, committing to convert the IVG.1M research reactor from HEU to LEU fuel in 2021, which will allow for that HEU to be removed in the future.
22	Kazakhstan	IGR	Pulsed Reactor	Operational according to the 2016 NAC study. Remove 2.9 kilograms of unirradiated HEU from the IGR research reactor, transport it hundreds of miles to a secure facility for processing, and downblend it to low enriched uranium (LEU). This activity fulfilled an agreement worked out between the US and Kazakhstan at the 2019 International Atomic Energy Agency (IAEA) General Conference. After being removed from the IGR research reactor in Kurchatov, the unirradiated HEU fuel was shipped by truck in 25 special transportation casks more than 200 miles to the Ulba Metallurgical Plant in Ust-Kamenogorsk.
23	Pakistan	PARR-2	MNSR	Operational (28 May 2018)
24	Russia	AKSAMIT	Critical Assembly	Operational according to the 2016 NAC study
25	Russia	BARS-4	Pulsed Reactor	Operational according to the 2016 NAC study
26	Russia	BARS-6	Pulsed Reactor	Operational according to the 2016 NAC study
27	Russia	BFS-1	Fast Critical Assembly	Operational according to the 2016 NAC study
28	Russia	BFS-2	Fast Critical Assembly	Operational according to the 2016 NAC study
29	Russia	BOR-60	Fast Reactor	Operational according to the 2016 NAC study
30	Russia	DELTA	Critical Assembly	Operational according to the 2016 NAC study

31	Russia	EFIR-2M	Critical Assembly	Operational according to the 2016 NAC study
32	Russia	GIDRA	Pulsed Reactor	Operational according to the 2016 NAC study
33	Russia	IRT-T	Steady State	Operational according to the 2016 NAC study
34	Russia	IVV-2M	Steady State	Operational according to the 2016 NAC study
35	Russia	KVANT	Critical Assembly	Operational according to the 2016 NAC study
36	Russia	MAKET	Critical Assembly	Operational according to the 2016 NAC study
37	Russia	MIR.M1	HPRR-Rus	Operational according to the 2016 NAC study
38	Russia	NARCISS-M2	Critical Assembly	Operational according to the 2016 NAC study
39	Russia	RBT-10/2	Steady State	Operational according to the 2016 NAC study
40	Russia	RBT-6	Steady State	Operational according to the 2016 NAC study
41	Russia	ST-1125	Critical Assembly	Operational according to the 2016 NAC study
42	Russia	ST-659	Critical Assembly	Operational according to the 2016 NAC study
43	Russia	WWR-M	Steady State	Extended shutdown (RRDB: 9 July 2014) but according to 2016 NAC study it is Operational
44	Russia	WWR-Ts	Steady State	Operational according to the 2016 NAC study
45	Russia	FS-2	Subcritical Assembly	Permanent shutdown (RRDB: 29 November 2016). However, license renewed on 19 December 2016 until 19 December 2021 (operator's website). Note that the reactor is operational according to the NAC 2016 study.
46	Russia	FM (Physical Model)-PIK	Critical Assembly	Operational (12 March 2018)
47	Russia	SM-3	Critical Assembly	Temporary shutdown (RRDB: 2 December 2019)
48	Russia	PIK	Steady State	Starting up expected to be operational. Reached its first criticality on 28 February 2011, power start-up on 8 February 2021
49	Russia	FKBN-2M	Critical assembly	Under modernization (As of 18 May 2018) Operational
50	Russia	IR-8	Steady State	Operational (RRDB: 19 June 2015)
51	Russia	K-1	Critical assembly	Operational according to the 2016 NAC study
52	Russia	OR	Steady State	Operational according to the 2016 NAC study
53	Russia	VIR-2M	Aqueous Solution Reactor	Operational (RRDB: 9 March 2018)

54	Russia	SM-3	Critical Assembly	Operational (RRDB: 13 March 2018)
55	Russia	IKAR-S	Critical Assembly	Operational (RRDB: 18 May 2018)
56	Russia	FKBN-2	Critical Assembly	Operational (RRDB: 18 May 2018)
57	Russia	BIGR	Fast Reactor	Operational (RRDB: 18 May 2018)
58	Russia	BARS-5	Fast, Pulsed Reactor	Operational (RRDB: 12 March 2018) Refurbished and ready to be restarted as bars-5m (16 April 2019, operator's website: http://vniitf.ru/article/issledovatelskie-reaktori-i-ustanovki)
59	Russia	IGRIK	Homogeneous Pulsed Reactor	Operational (RRDB: 12 March 2018) Operational aka igrik-2 (16 April 2019, operator's website: http://vniitf.ru/article/issledovatelskie-reaktori-i-ustanovki)
60	Russia	MIR.M1	HPRR-Rus	Operational (RRDB: 15 June 2017) Operator's website: "the scheduled lifetime of the reactor is until 2020" (http://www.niiar.ru/node/226)
61	Russia	IRV-M2	Pool type	Under reconstruction in 2017 (RRDB) Operator's website mentions it too: http://www.niipriborov.ru/devices) u-235: 36%
62	Russia	BR-1M	Pulsed Reactor	Operational (RRDB: 13 March 2018)
63	Russia	BR-K1	Pulsed Reactor	Operational (RRDB: 13 March 2018)
64	Russia	GIR-2	Pulsed Reactor	Operational (RRDB: 18 May 2018)
65	Russia	FBR-L (EBR-L)	Pulsed Reactor	Operational (RRDB: 12 March 2018)
66	Russia	YAGUAR	Solution Pulsed Reactor	Operational (RRDB: 12 March 2018; operator's website, 16 April 2019: http://vniitf.ru/article/issledovatelskie-reaktori-i-ustanovki)
67	Russia	UG	Subcritical Assembly	Operational (RRDB: 6 June 2017)
68	Russia	BR-10	Fast Reactor	Permanent shutdown (RRDB: 9 March 2018)
69	Russia	IBR-2M	Fast, pulsed reactor	Operational (RRDB: 12 March 2018)
70	Russia	Astra	Critical Assembly	Operational as of March 2018
71	Syria	SRR-1	MNSR	Operational (21 May 2018)
72	United States	GE-NTR	Steady State	Operational according to the 2016 NAC study
73	United States	ATR	HPRR-US	Operational. Committed to convert once fuel is available. Completed preliminary designs for U-10Mo fuel.

74	United States	MITR-II	HPRR-US	Operational. Committed to convert once fuel is available. Submitted their Preliminary Safety Analysis Reports (PSAR's) for conversion.
75	United States	MURR	HPRR-US	Operational. Committed to convert once fuel is available. Submitted their Preliminary Safety Analysis Reports (PSAR's) for conversion.
76	United States	NBSR	HPRR-US	Operational. Committed to convert once fuel is available. Submitted their Preliminary Safety Analysis Reports (PSAR's) for conversion.
77	United States	HFIR	HPRR-US	Operational. Committed to convert once fuel is available
78	United States	TREAT	Steady State	Operational according to the 2016 NAC study
79	United States	ATR-C	Critical Assembly	Operational. Committed to convert once fuel is available. Completed preliminary designs for U-10Mo fuel.
80	United States	HFIR	HPRR-US	Operational. Committed to convert once fuel is available. Completed preliminary designs for U-10Mo fuel.

Appendix 4

Research Reactor Operator Perceptions on Conversion

In 2013 CNS carried out a survey of 33 research reactor operators whose research reactors have been converted under the RERTR program from HEU fuel to LEU. The report of the study was never published in its entirety, but the findings were reported at the European Research Reactor Conference, Ljubljana, Slovenia, April 1, 2014.

The survey was conducted to determine the effect of conversion on fuel supply costs, security, understanding and utility of the reactor in order to provide other operators considering conversion with a better understanding of the conversion experience. It also sought to determine if the RERTR's principles of conversion (described in the report) had been adhered to in the process. Most of the questions in the survey had both a qualitative and a quantitative component. A key finding of the survey was that in many respects the perception of conversion by the operators appears to be overwhelmingly positive. Fewer than 8% of the reactor operators perceived that conversion led to even a "slight detriment" in the overall operation of their reactors. To be sure, some reactors did perceive some downsides to conversion. **For example, a third of the operators cited a change in the flux of their reactor as a drawback because it affected their ability to conduct experiments or carry out commercial work such as silicon doping or production of medical isotopes.** A third of the operators also perceived that conversion led to an increase in fuel costs, although the accuracy of this perception is not clear.

Yet operators overwhelmingly perceived any negative impacts to be outweighed by positive ones. The survey found that the greatest benefit of conversion perceived by the reactor operators was that public acceptance of reactors increased, since the reactor after conversion poses less of a proliferation concern. The operators recognized that this was an opportunity to communicate with the local community about the benefits and role of a nuclear reactor in society. The second greatest benefit expressed by the operators was the decrease in security cost and the freeing up of space in the spent fuel pool essentially extending the life of the reactor. Clearly, an important finding from this study is that **the perception of an obligatory "flux penalty" often regarded as a serious obstacle to conversion is not determinative**. The decision on conversion must be made by weighing multiple concerns such as the cost of fuel, fuel disposition, and effect on the uses of the reactor, training, education and outreach. The survey also led to several additional recommendations. Given the perception of some operators (rightly or wrongly) of increased fuel costs from conversion, NNSA should consider an in-depth study of this issue which seeks to tease out whether in fact (inflation-adjusted) changes in operator fuel costs, have occurred, their cause, and possible remedies. Finally, NNSA officials should consider means of further boosting the public relations appeal of reactor conversion. One recommendation is to develop ready-made pedagogical material that might help facilitate discussions on the importance of conversion with the local public, and to provide more technical material for the students of reactors that intend to convert. These materials could then be distributed by the reactors' staff. The value of enhancing public diplomacy which trumpets local reactor officials' contributions to global security might also be considered.

About the Authors

Miles Pomper

Miles Pomper is Senior Fellow in the Washington D.C. office of the James Martin Center for Nonproliferation Studies (CNS) of the Middlebury Institue of International Studies at Monterey and an expert in nuclear security. He is the author of numerous publications on HEU minimization and helped draft the HEU “gift basket” calling for the ultimate elimination of civilian HEU that Norway, Netherlands, and 20 other states announced at the 2016 Nuclear Security Summit. For six years, he served as chair of the Fissile Materials Working Group, a coalition of more than 80 organizations and individuals worldwide working to combat nuclear terrorism.

Ferenc Dalnoki-Veress

Ferenc Dalnoki-Veress is a scientist-in-residence at the James Martin Center for Nonproliferation Studies and Adjunct Professor at the Middlebury Institute for International Studies at Monterey. He holds an MSc and PhD in high energy physics from Carleton University, Canada, specializing in ultra-low radioactivity background detectors, and has professional experience in the field of astroparticle physics, primarily neutrino physics, where he has contributed to several major discoveries in the field. Dalnoki-Veress was a member of the Sudbury Neutrino Observatory Collaboration that won the 2015 Nobel Prize in physics and is a laureate along with his team of the 2016 Breakthrough Prize in Physics. He has contributed to more than forty articles in refereed and non-refereed journals. At the Institute, he focuses on the proliferation of fissile materials, nuclear spent fuel management, emerging technologies and verification of nuclear weapons. In March 2021 he published a co-authored book titled “Nuclear Choices for the Twenty-First Century: A Citizens Guide” published by MIT Press.

Margarita Kalinina-Pohl

Margarita Kalinina-Pohl is the Senior Program Manager/Research Associate at the James Martin Center (CNS) for Nonproliferation Studies at Middlebury Institute of International Studies (Monterey, California). During her 22-year career at CNS, Ms. Kalinina-Pohl held various positions at CNS, including managing CNS regional office in Almaty, Kazakhstan.

Margarita's current research interests include nuclear and radiological security. She is also engaged in several nonproliferation education and capacity building projects and initiatives aimed at promoting and empowering women in the nuclear field.

She authored and co-authored articles and reports on nuclear and radiological security, problems of uranium tailings in Central Asia and Soviet nuclear legacy.

Artem Lazarev

Artem Lazarev joined the VCDNP as a Research Associate in October 2017. Prior to that, he completed an internship at the Office of Legal Affairs of the International Atomic Energy Agency (IAEA) dealing with the legal aspects of nuclear safety, security and liability. Mr. Lazarev also worked as a lawyer at the European Court of Human Rights from 2012 to 2016 and has held several other legal posts in Russia and Spain.

Mr. Lazarev completed his PhD in International Law from the University Pompeu Fabra (UPF) in September 2017. His dissertation focused on the evolution of the legal aspects of the IAEA safeguards and their application to Iran. Previously he obtained a Master's degree in Human Rights Law from the University of Strasbourg (2016), an Advanced Master's degree in Legal Sciences at UPF (2011) and degrees in International Relations and in Law from Tomsk State University in Russia (2007 and 2008 respectively).

Occasional Papers from CNS

#44 • Eyes on U: Opportunities, Challenges, and Limits of Remote Sensing for Monitoring Uranium Mining and Milling

#43 • North Korea's International Scientific Collaborations: Their Scope, Scale, and Potential Dual-Use and Military Significance

#42 • The Other Fissile Material: Strengthening National and International Plutonium Management Approaches

#41 • Monitoring Uranium Mining and Milling in India and Pakistan through Remote Sensing Imagery

#40 • Monitoring Uranium Mining and Milling in China and North Korea through Remote Sensing Imagery

#39 • Safeguards and Verification in Inaccessible Territories

#38 • Geo4Nonpro 2.0

#37 • All the World Is Staged: An Analysis of Social Media Influence Operations against US Counterproliferation Efforts in Syria

#36 • North Korea's Information Technology Networks

#35 • Countering North Korean Procurement Networks Through Financial Measures: The Role of Southeast Asia

#34 • Open-Source Monitoring of Uranium Mining and Milling for Nuclear Nonproliferation Applications

#33 • WMD Proliferation Risks at the Nexus of 3D Printing and DIY Communities

#32 • Taiwan's Export Control System: Overview and Recommendations

#31 • Revisiting Compliance in the Biological Weapons Convention

#30 • Crowdsourcing Systems and Potential Applications in Nonproliferation

#29 • The Verification Clearinghouse: Debunking Websites and the Potential for Public Nonproliferation Monitoring

#28 • Geo4nonpro.org: A Geospatial Crowdsourcing Platform for WMD Verification

#27 • Searching for Illicit Dual Use Items in Online Marketplaces: A Semi-Automated Approach

#26 • 2016 Symposium Findings on Export Control of Emerging Biotechnologies

#25 • Outlawing State-Sponsored Nuclear Procurement Programs and Recovery of Misappropriated Nuclear Goods

#24 • Strengthening the ROK-US Nuclear Partnership

#23 • Replacing High-Risk Radiological Materials

#22 • A Blueprint to a Middle East WMD-Free Zone

#21 • Biotechnology E-commerce: A Disruptive Challenge to Biological Arms Control

#20 • Countering Nuclear Commodity Smuggling: A System of Systems

#19 • Alternatives to High-Risk Radiological Sources

#18 • Stories of the Soviet Anti-Plague System

#17 • Ugly Truths: Saddam Hussein and Other Insiders on Iraq's Covert Bioweapons

#16 • Rethinking Spent Fuel Management in South Korea

#15 • Engaging China and Russia on Nuclear Disarmament

#14 • Nuclear Challenges and Policy Options for the Next US Administration

#13 • Trafficking Networks for Chemical Weapons Precursors: Lessons from the 1980s Iran-Iraq War

#12 • New Challenges in Missile Proliferation, Missile Defense, and Space Security

#11 • Commercial Radioactive Sources: Surveying the Security Risks

#10 • Future Security in Space: Commercial, Military, and Arms Control Trade-Offs

#09 • The 1971 Smallpox Epidemic in Aralsk, Kazakhstan, and the Soviet Biological Warfare Program

#08 • After 9/11: Preventing Mass Destruction Terrorism and Weapons Proliferation

#07 • Missile Proliferation and Defences: Problems and Prospects

#06 • WMD Threats 2001: Critical Choices for the Bush Administration

#05 • International Perspectives on Ballistic Missile Proliferation and Defenses

#04 • Proliferation Challenges and Nonproliferation Opportunities for New Administrations

#03 • Nonproliferation Regimes at Risk

#02 • A History of Ballistic Missile Development in the DPRK

#01 • Former Soviet Biological Weapons Facilities in Kazakhstan: Past, Present, and Future

nonproliferation.org

Middlebury Institute *of* International Studies at Monterey
James Martin Center for Nonproliferation Studies