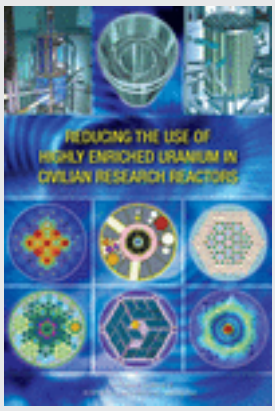

Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors

DETAILS

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Cover: graphical images of research reactor cores (clockwise from top-left corner then center): Réacteur à Haut Flux (RHF) core at Institut Laue-Langevin (ILL), Grenoble, France (Image courtesy of ILL/Symetrix); the Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM-II) core (courtesy of Technische Universität München); the Neutron Beam Split-Core Reactor (NBSR) core (courtesy of the National Institute for Standards and Technology Center for Neutron Research); the MIR.M1 core (courtesy of the Joint Stock Company "State Scientific Center—Research Institute of Atomic Reactors," Russia); the High Flux Isotope Reactor (HFIR) core (courtesy of Oak Ridge National Laboratory); the Massachusetts Institute of Technology Nuclear Research Reactor (MITR-II) core (courtesy of Massachusetts Institute of Technology's Nuclear Reactor Laboratory); the Belgian Reactor 2 (BR2) core (courtesy of Studiecentrum voor Kernenergie·Centre d'Étude de l'Énergie Nucléaire); the Advanced Test Reactor (ATR) core (courtesy of Idaho National Laboratory); and the Missouri University Research Reactor (MURR) core (courtesy of the University of Missouri Research Reactor Center).

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Of course, the success of this project is due in large part to the high-quality of presentations provided by the speakers and presenters, who are listed in Appendix C.

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the Academies in making its published report as sound as possible and will ensure that this report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their participation in the review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions and recommendations of this report, nor did they see the final draft of the report before its release. The review of this report was overseen by John F. Ahearne, Sigma Xi, The Scientific Research Society (retired), and Milton Levenson, independent consultant and formerly of Bechtel International (retired). They were responsible for making certain that an independent examination of this report was carried out in accordance with institu-

tional procedures and that all review comments were considered carefully. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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The expertise needed to cover the areas within our scope was remarkably broad, and the committee membership reflected this diversity. The committee members brought to the study deep knowledge of materials science; nonproliferation policy; nuclear engineering; research reactor fuel design, fabrication, and qualification; reactor operations; research reactor performance analysis (neutronics, thermal hydraulic analysis, accident analysis); research reactor regulation; as well as invaluable international and historical perspectives.

Our meetings were characterized by a rare combination of wisdom gained from years of experience in the field, deep curiosity about things that were new to us, and a willingness to challenge conventional thinking. The sometimes spirited dialogue was always characterized by a level of respect and collegiality that is too often elusive in difficult conversations. The opportunity to lead this distinguished group has truly been a privilege. I thank the members of the committee for their dedication, willingness to teach and to learn, and unfailing good humor.

Julia Phillips, *Chair*

Contents

Summary

This report results from a congressionally mandated study (P.L. 112-239, Section 3178[1]) to assess the current status of and progress toward eliminating highly enriched uranium (HEU)[2] use in fuel for civilian research and test reactors. The complete study charge is given in Box 1.1.

The continued presence of HEU in civilian installations such as research reactors[3] poses a threat to national and international security. Minimization, and ultimately elimination, of HEU in civilian research reactors worldwide has been a goal of U.S. policy and programs since 1978. Today, 74 civilian research reactors around the world, including 8 in the United States, use or are planning to use HEU fuel. Encouragingly, since the last National Academies of Sciences, Engineering, and Medicine (the Academies) report on this topic in 2009 (NRC, 2009), 28 reactors have been either shut down or converted from HEU to low enriched uranium (LEU) fuel.[4] Despite this progress, the large number of remaining HEU-fueled reactors demonstrates

[1] The American Medical Isotopes Act of 2012, http://www.gpo.gov/fdsys/pkg/PLAW-112publ239/html/PLAW-112publ239.htm.

[2] HEU is defined as uranium enriched to 20 percent or greater in the isotope ^{235}U; weapon-grade HEU (W-HEU) is enriched to 90 percent or greater.

[3] This report refers to "research and test reactors" as simply "research reactors." The U.S. Nuclear Regulatory Commission (USNRC) differentiates between a research and test reactor by thermal output power level; research reactors operate at 10 megawatts or less, and test reactors operate above this level. For the purposes of this report, this differentiation is not important. For more information on the USNRC's regulation of research and test reactors, see http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/research-reactors-bg.html.

[4] LEU is uranium enriched to less than 20 percent in the isotope ^{235}U.

that an HEU minimization program continues to be needed on a worldwide scale.

Research reactors are important to the U.S. and global scientific and technical enterprise. They fulfill important missions ranging from education to basic scientific research to medical isotope supply to patient treatment. Other mechanisms for producing neutrons with similar spectra and flux levels to fulfill these missions do not currently exist (Finding 3). These characteristics guarantee the enduring importance of research reactors in science and technology.

Most research reactors in use around the world are many decades old. Many, including all of the high performance research reactors (HPRRs[5]) operating in the United States, were commissioned in the 1950s and 1960s; the youngest U.S. HPRR is more than 45 years old. Additionally, the U.S.-based HPRRs (USHPRRs) are managed by different offices and agencies. Given the ages of these reactors and evolving needs for neutrons, it is not surprising that the missions of some USHPRRs have evolved. The capabilities of these reactors have accommodated changing user needs and an expanded user base, with the consequence that reactors are sometimes not specifically designed for current missions (Finding 4). No new USHPRRs are currently planned; therefore, for the foreseeable future, maintenance and relicensing of the existing reactors is the only viable option for continued reactor availability. The situation is quite different in Europe, where the youngest HPRRs are as little as 12 years old and where additional research reactors are under construction or active planning. In short, European countries are developing and executing a strategy for ensuring the continued availability of HPRRs to meet their future needs; the United States has no such strategy and seems to expect the current HPRRs to operate indefinitely.

Conversion of the remaining research reactors has proven to be significantly more difficult than envisioned when the U.S. conversion program began nearly 40 years ago. The nearly 20-year time line to conversion that is currently estimated for some HPRRs is much longer than originally estimated and coincides with their relicensing around 2030. At that time the USHPRRs will be on average 65 years old. Because of the coincidence of relicensing, conversion, and aging issues of the current USHPRRs, it is reasonable to compare the benefit of converting/retrofitting the current fleet of USHPRRs against designing and building new research reactors that use

[5] HPRRs are, in the most general sense of the definition, reactors for which available LEU fuels do not currently exist to support conversion without an effect on their performance (Roglans, written communication, September 2015). Editorial note: This report follows convention used by the Department of Energy (DOE) and others by not hyphenating "high performance" in the phrase "high performance research reactors."

LEU fuel and address the critical missions that current reactors support. In fact, the Department of Energy (DOE) has performed such an analysis, but DOE has authority for one-half of the USHPRRs and this analysis was focused on DOE missions (e.g., research reactors to support the next generation nuclear energy systems). The Office of Science and Technology Policy has the authority to consider an analysis of all USHPRRs and the variety of missions they support. Nevertheless, there is no overarching, long-term, cross-agency strategy for meeting enduring U.S. needs for research reactors (Finding 5).

Recommendation 1: The U.S. Office of Science and Technology Policy should take the lead in developing a 50-year interagency strategy that enumerates and evaluates the importance of anticipated U.S. civilian needs for neutrons and provides a roadmap for how these can best be provided by reactors and other sources that do not use highly enriched uranium.

There are significant technical and nontechnical obstacles associated with eliminating HEU from civilian research reactors. Most of the technical obstacles relate to developing and qualifying very high-density fuel (based on a uranium-molybdenum [UMo] alloy) needed to convert the remaining HPRRs. The timescale for designing, producing, qualifying, and using such fuel to complete conversions is now estimated to be around 15–20 years for U.S. research reactors, resulting in nearly two decades of continued reliance on W-HEU. The fuel type being pursued by the United States faces more manufacturing challenges for qualification than the type being developed in Europe and South Korea and, therefore, the development and qualification time lines have higher uncertainty and risk (Finding 6).

A high-density LEU dispersion fuel is being pursued by a consortium of European countries and separate efforts in South Korea and Russia. In terms of microstructure and manufacturing processes, the new LEU dispersion fuel, also a UMo alloy, is similar to existing, qualified fuels. However, the U.S. fuel development effort requires fabrication methods qualitatively different from those used for any existing fuel. This approach, if successful, will yield a very high-density LEU fuel that can be used in all USHPRRs.

The fuels under development in Europe and South Korea might be suitable for the conversion of some but not all USHPRRs.[6] Furthermore, the fuel

[6] USHPRRs with lower power density requirements include University of Missouri Research Reactor (MURR), Massachusetts Institute of Technology Reactor (MITR-II), and the Neutron Beam Split-Core Reactor (NBSR); the USHPRRs with the highest power density requirements are the Advanced Test Reactor (ATR) and its critical assembly (ATR-C) and the High Flux Isotope Reactor (HFIR).

being qualified by South Korea may offer modest acceleration in the anticipated conversion time lines for USHPRRs with lower power density requirements. If these fuels become successfully qualified, then they can be used to mitigate technical risks in the current U.S. monolithic fuel development time line by providing alternate high-density LEU dispersion fuel options for those USHPRRs with lower power density requirements (Finding 8).

Recommendation 2: Despite a timescale that is now understood to be much longer than initially expected, the United States should continue to develop a very high-density, low enriched uranium (LEU) fuel to convert as soon as possible the existing generation of U.S. high performance research reactors to LEU operation as well as to enable a new generation of research reactors.

Recommendation 3: The United States should closely monitor the development of low enriched uranium (LEU) dispersion fuels (e.g., in Europe, South Korea, and Russia) and evaluate their possible use as backup options for U.S. high performance research reactor conversions if there are unexpected delays in the development of the U.S. monolithic fuel.

The economic viability of high-density LEU fuel is highly uncertain and is a source of significant concern to the operators of HPRRs worldwide (Finding 7). Not enough is known about the final manufacturing processes for these fuels, particularly for UMo monolithic fuel, including process complexity and yield, to be able to make definitive estimates of fuel cost. However, assuming the current cost model for research reactor fuel continues, one thing is clear: fixed costs associated with the maintenance of a high-density LEU manufacturing line are expected to be borne by the reactor facilities that use the fuel. If the number of research reactors using high-density LEU fuel is markedly different from the number using today's HEU fuel, or if even one of the reactors that uses large quantities of fuel does not convert, then the cost of high-density LEU fuel could easily become prohibitive for the remaining reactors.

Although DOE has been actively engaged in reactor conversions and shutdowns around the world, there has not been a conversion of a civilian research reactor to LEU fuel in the United States since 2009. This lack of conversions, combined with the long time line for conversion of the USHPRRs, could call into question the level of U.S. commitment to conversion of its own reactors. Based on rough approximations made by the committee, all HPRRs in the United States and Europe but one could probably convert using existing, qualified LEU silicide fuel at enrichments of 45 percent or less without significant impact to the missions they sup-

port; some of the reactors could use fuel enriched to less than 30 percent. European HPRRs have performed calculations to assess feasibility of this option, but the United States has not (Finding 9).

Recommendation 4: To achieve the goal of using as little highly enriched uranium as possible during the many years that it will take to design and qualify appropriate low enriched uranium (LEU) fuel, the United States should pursue an interim solution that reduces the civilian use of weapon-grade material.

- **a. During this interim period, high performance research reactors should use dispersion silicide fuel enriched to the lowest practical level, which can be produced with technologies already known to be reliable. The precise enrichment level can be quickly determined by a focused, small-scale study.**
- **b. The United States should downblend the remaining 20 metric tons of highly enriched uranium (HEU) designated for civilian research reactor use to this lowest practical enrichment level as soon as it has been determined.**
- **c. The interim solution should be pursued in a way that does not compromise the long-term goal of eliminating HEU usage in civilian applications.**

Although the obstacles to conversion of HPRRs are predominantly technical, the obstacles to the conversion of other research reactors are frequently nontechnical. One country of particular concern is Russia. Despite considerable reductions in the number of civilian research reactors fueled by HEU since 2009, Russia remains home to greater than 40 percent of the HEU-fueled civilian research reactors identified by this committee. 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. Notably the number of these types of facilities has significantly decreased during the past few years. Nearly all research reactors located outside of Russia that use Russian nuclear fuel have been converted to LEU, with most of the Russian-origin HEU returned to Russia. Converting most of the remaining Russian research reactors is possible with existing or soon-to-be-qualified LEU fuel. However, conversion of its domestic research reactors is not a high national priority for Russia (Finding 10).

The Russian-U.S. collaboration on research reactor conversion that progressed for several decades has all but ceased during the past year. Funding of conversions for Russian domestic research reactors has been drastically reduced. Previously, the United States (through DOE) funded these conversions, but the U.S. and Russian governments have mutually ended this program and only limited interaction remains. One particularly

valuable aspect of these collaborations was the development of long-term relationships between U.S. and Russian scientists (Finding 12). Russia is, however, very interested in exporting its nuclear technology, including LEU fuel and radioisotopes. This may be a Russian priority that can be leveraged in continuing bilateral efforts on HEU minimization. Given current international relations in general, and the state of U.S.-Russian relations in particular, the United States and the international community have little influence on Russian prioritization of its domestic civilian research reactor conversions (Finding 13).

Recommendation 5: The United States should encourage and facilitate periodic workshops and meetings that especially engage U.S. and Russian scientists and engineers to continue scientific exchanges and interactions that formed the basis for previous progress in highly enriched uranium (HEU) minimization. These interactions should also seek areas of mutual interest that would result in HEU minimization, jointly study the risks and benefits of low enriched uranium conversion, and identify possible collaborations.

The U.S. Office of Conversion, a component of the recently formed Office of Material Management and Minimization (M^3),[7] is focused on surmounting the significant technical challenges associated with converting the HPRRs as well as completing the conversion of the remaining HEU-fueled reactors worldwide. The conversion program currently reports annual progress toward its goal of eliminating HEU from civilian research reactors by counting the number of reactors using HEU that have either converted or shut down.[8] This metric does not fully convey progress toward minimizing and eliminating the use of HEU fuel for research reactors for three reasons. First, the program definition of a "converted" reactor is one in which at least one LEU fuel element has been inserted. In the case of some reactors, HEU fuel remains in the reactor until the conversion is complete.[9] Second, reporting the number of reactors converted or shut down

[7] The United States has had a research reactor conversion program since 1978, but it has undergone a number of reorganizations (see Chapter 2). The most recent change was the dissolution of the Global Threat Reduction Initiative (GTRI) and its Convert Program and the creation of M^3 and the Office of Conversion.

[8] These annual reports of progress are made to Congress through budgetary request documents. Additionally, the Office of Conversion routinely reports its progress at annual international meetings such as the Reduced Enrichment for Research and Test Reactors conference or the European Research Reactor Fuel Management conference.

[9] For some reactor cores, fuel replenishment takes place one fuel element at a time. Fully converting a core to LEU fuel can take years, depending on the refueling schedule of the reactor.

does not measure how much HEU fuel is in place at research reactor sites, whether in core or in storage (fresh or spent fuel, respectively). Third, the largest fraction of HEU annual consumption is made by a small number of reactors. No metric provides data on the reduction of the annual consumption of HEU in civilian research reactors.

Recommendation 6: The Material Management and Minimization's Office of Conversion should augment its annual progress reports to include the following:

- **a. Identification of the number of conversions in progress (i.e., with at least one low enriched uranium [LEU] assembly inserted into the core);**
- **b. Identification of the number of conversions completed, including the removal of highly enriched uranium (HEU) fresh and spent fuel from the site;**
- **c. Separate reporting of reactors that have fully converted to LEU from those that have been verified as shut down;**
- **d. Reduction of the aggregated inventory of HEU fuel at reactor sites (including shutdown reactors) attributable to the conversion program; and**
- **e. Reduction in the amount of weapon-grade HEU fuel shipped to HEU-fueled research reactors during the reporting period attributable to the conversion program.**

The technical setbacks and increasingly longer time lines for conversion of USHPRRs emphasize the need to develop a robust project management strategy along with regular independent technical and programmatic evaluations (Finding 17). Review teams have been established by the M^3 Office of Conversion in recent years to guide program management decisions. Three review teams have been formed to focus on strategic review, cost, and fuel development. Of these three teams, only the fuel development team reviews technical aspects of the program (and its charge is limited to the fuel development pillar). The committee found that the review of fuel development, although technically sound, was not performed by a team with the appropriate independence and institutional diversity needed for critical evaluation and feedback (Finding 18).

Recommendation 7: In-depth independent technical review of each aspect of the fuel life-cycle (from fuel development, fabrication, recycling, and spent fuel management), as well as integration of the technical components, should be conducted to ensure that the newly instituted risk and systems analysis capabilities within the Material Management and Minimization Office of Conversion develop into

robust project and risk management. These reviews should be conducted by qualified, independent, and diverse external experts.

The M^3 Office of Conversion has recently initiated a number of important changes in its management of the program, but the impact of these changes could not yet be assessed.

1

Background and Study Task

This report assesses the status of and progress toward eliminating the worldwide use of highly enriched uranium (HEU) fuel in civilian research and test reactors. Elimination of HEU[1] fuel in research and test reactors (hereafter, referred to as simply "research reactors"[2]) is one of several efforts that support the nuclear nonproliferation goal of minimizing or eliminating the use of weapon-usable nuclear material in civilian applications. The main civilian applications that use special nuclear material (primarily HEU) are research reactors, targets for medical isotope production, and propulsion systems for remote missions. Research reactors use HEU-based fuel to achieve a large flux of neutrons with which to perform basic research, materials studies, and materials production. Molybdenum-99 (^{99}Mo), the precursor of the most commonly used medical isotope, is produced primarily by irradiating HEU targets.[3] Propulsion systems designed for long-duration, remote missions (e.g., missions involving spacecraft or

[1] HEU is defined as uranium enriched to 20 percent or higher in the isotope ^{235}U; weapon-grade HEU (W-HEU) is enriched to 90 percent or higher (e.g., see Glaser, 2006).

[2] The U.S. Nuclear Regulatory Commission (USNRC) differentiates between a research and a test reactor by thermal output power level; research reactors operate at 10 megawatts or less, and test reactors operate above this level. For the purposes of this report, this differentiation is not important. For more information on the USNRC's regulation of research and test reactors, see http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/research-reactors-bg.html.

[3] A common medical isotope used for medical diagnostic studies is a metastable state of technetium (technetium-99m, ^{99m}Tc). ^{99m}Tc can be produced by irradiating HEU targets in reactors, resulting in the fission of ^{235}U to molybdenum-99 (which has a 66-hour half-life), which in turn decays to ^{99m}Tc (with a 6-hour half-life).

icebreakers) use HEU-fueled nuclear reactors as a long-lived steady power source. Of these three main applications, research reactors use the vast majority of civilian HEU.

Compared to nuclear power reactors, research reactors require far less fuel and operate at much lower power levels and temperatures. However, to accomplish their basic mission of producing large numbers of neutrons over a sustained period of time, HEU fuel is used because, with currently qualified fuels, it allows for the design of compact reactors with higher neutron fluxes.

Research reactors are used for training and education, irradiation of materials, and extracted beam applications (IAEA, 2014). Training and educating the next generation of nuclear scientists and reactor operators is their most common mission and therefore many of them are located at universities. Irradiation of samples and materials within and near the core of the research reactor is important for materials testing and applications that require transmutation[4]—the changing of one element into another, in this case induced by the radiation inside the reactor. Irradiating materials in the intense radiation environment of a research reactor reveals how their engineering properties (e.g., strength, swelling, and ductility) change and deteriorate under such conditions, a critical test for selecting and qualifying the materials needed to safely harness nuclear power. The production of radioisotopes through transmutation is useful in industry and medicine. In extracted beam applications, neutrons emitted from the core of a reactor travel through beam tubes to experimental stations outside of the core, where they can be used for basic scientific studies of materials under a wide variety of temperatures, pressures, magnetic fields, and other relevant conditions, as discussed in Chapter 3.

A large neutron flux is essential for most of these applications, whether for efficient material production or usable signal-to-noise ratios in scientific investigations. The high density of ^{235}U in an HEU reactor fuel leads to a compact core and enables high neutron flux per gram of material, making it an attractive fuel for these applications. Unfortunately, this same property makes HEU attractive as the core component in a rudimentary nuclear weapon.

Since the late 1970s, government and international programs have aimed to reduce the use of HEU fuel in research reactors (see details of these programs in Chapters 2 and 5). These programs have focused on the conversion of reactor fuel from HEU to low enriched uranium (LEU).[5] From a non-

[4] Transmutation occurs when a neutron bombarding an atomic nucleus is absorbed, changing it into a different isotope of the same element, or when a nucleus fissions, producing two or more different elements. Other processes are involved in transmutation; see Glossary for a more detailed definition.

[5] LEU is defined as uranium enriched to less than 20 percent in the isotope ^{235}U.

proliferation standpoint, the closure of an HEU-fueled reactor would accomplish the same goal. However, conversion programs seek the cooperation of the operators via assurances or incentives to maintain performance and operating costs. Closure or shutdown is not a goal of conversion programs, but it may be an unintended consequence once decision or policy makers consider nonproliferation goals, conversion costs, or reactor aging (see Chapter 2).

MOTIVATION FOR THE STUDY

This study was mandated by Congress in the American Medical Isotopes Production Act of 2012. Section 3178 of the act states

> The Secretary [of Energy] shall enter into an arrangement with the National Academy of Sciences [the Academies] to conduct . . . an assessment of the progress made by the Department [of Energy] and others to eliminate all worldwide use of highly enriched uranium in reactor fuel, reactor targets, and medical isotope production facilities.[6]

During negotiations between the National Academies of Sciences, Engineering, and Medicine (the Academies) and the National Nuclear Security Administration (NNSA),[7] it was agreed that two studies would be conducted to support this mandate: one on medical isotope production without HEU targets and the other on the conversion of research reactors to LEU. These studies were separated because efforts to eliminate HEU use in research reactor fuel and medical isotope production targets are proceeding along independent lines, engage largely different technical communities, and confront different technical, economic, and regulatory challenges. The status of and progress toward the production of medical isotopes without the use of HEU is the subject of a separate but parallel Academies study and report.[8] The statement of task for the research reactor conversion study was developed to be consistent with the congressional mandate and analogous to the medical isotope study. The statement of task can be found in Box 1.1 and in Appendix A.

STRATEGY TO ADDRESS THE STUDY CHARGE

This study was carried out by a committee of experts appointed by the Academies. The committee consists of 10 members and 1 technical consul-

[6] The full text of the bill pertinent to this study is available at http://www.gpo.gov/fdsys/pkg/BILLS-112hr4310enr/pdf/BILLS-112hr4310enr.pdf (accessed December 15, 2014).

[7] The NNSA is a semi-autonomous agency within the Department of Energy (DOE) and is the organization sponsoring this study.

[8] Information about the study can be found at http://www8.nationalacademies.org/cp/projectview.aspx?key=49673.

BOX 1.1
Statement of Task

An ad hoc committee will conduct a study and prepare a report with findings and recommendations on the current status of and progress toward eliminating highly enriched uranium (HEU) use in fuel for civilian research and test reactors. This study will provide

1. A list of civilian research and test reactors that operate using HEU fuel.
2. A review of civilian research and test reactor status over the past 5 years, including new HEU-fueled reactors that were planned, under construction, or commissioned; HEU-fueled reactors that were shut down and/or decommissioned; and HEU-fueled reactors that were converted to low enriched uranium (LEU).
3. An assessment of the progress being made by the Department of Energy and others to eliminate worldwide use of HEU in fuel for civilian research and test reactors. This assessment should identify key technical and nontechnical factors responsible for the successful conversion of reactors from HEU to LEU fuel; key obstacles to converting the remaining HEU-fueled reactors; and steps that could be taken to overcome the identified obstacles.

tant with expertise that spans the issues relevant to the study task: materials science; nonproliferation policy; nuclear engineering; research reactor fuel design, fabrication, and qualification; reactor operations; research reactor performance analysis (e.g., neutronics, thermal hydraulic analysis, accident analysis); and research reactor regulation. In selecting the membership of this committee, the Academies sought to obtain a balanced committee composed of members with relevant disciplinary expertise and no current connection to the NNSA's Office of Material Management and Minimization (M^3) or nuclear regulatory agencies. The committee chair is an academy member with demonstrated leadership capabilities, but she has no direct experience in nuclear research reactor conversion or fuel development. Biographical sketches of the committee members and technical consultant are provided in Appendix B.

The committee contacted a broad variety of parties and agencies to obtain information to address its study charge. The committee held seven meetings to receive information from subject matter experts, representatives from research reactor facilities, user communities, and federal agency staff (Appendix C). A joint International Atomic Energy Agency (IAEA) and Academies meeting was held to develop a publicly available list of existing

civilian research reactors worldwide currently using HEU fuel.[9] Appendix E provides a synopsis of the joint IAEA–Academies meeting and the resulting list of HEU-fueled research reactors.

Committee members toured domestic research reactor facilities in conjunction with their data-gathering sessions: the Advanced Test Reactor (ATR), its critical assembly (ATR-C), and the Transient Reactor Test Facility in Idaho Falls, Idaho; the University of Missouri Research Reactor in Columbia, Missouri; the Neutron Beam Split-Core Reactor at the National Institute of Standards and Technology Center for Neutron Research in Gaithersburg, Maryland; the High Flux Isotope Reactor and the Spallation Neutron Source in Oak Ridge, Tennessee; and the Y-12 National Security Complex LEU fuel fabrication line, also in Oak Ridge. A subgroup of the committee[10] toured Babcock and Wilcox Technologies' (BWXT's) fuel fabrication facility and new production line for uranium-molybdenum (UMo, also known as "U-moly") monolithic fuel in Lynchburg, Virginia.

Other subgroups of the committee toured a variety of foreign reactors: the MARIA reactor in Poland[11]; the Forschungs-Neutronenquelle Heinz Maier-Leibnitz-II reactor in Germany; Belgian Reactor-2 in Belgium; the High Flux Reactor in the Netherlands; the High Flux Reactor at the Institut Laue-Langevin in France; and MIR.M1, BOR-60, SM-3, RBT-6, and RBT-10/2 at the Joint Stock Company "State Scientific Center—Research Institute of Atomic Reactors" in Dimitrovgrad, Russia. These trips also included meetings with representatives from the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) and Compagnie pour l'Etude et la Réalisation de Combustibles (the subsidiary of AREVA responsible for research reactor fuel manufacture) in Paris and representatives from the Russian Academy of Sciences, Center for Energy and Security Studies, and Rosatom (the Russian national nuclear corporation) in Moscow. During the site visits and tours, committee members discussed opportunities and challenges associated with research reactor fuel conversion and fabrication

[9] This joint meeting was the result of discussions between the Academies and the IAEA regarding two similar but previously disconnected efforts. Task 1 from this study's statement of task directs the committee to establish a list of research reactors currently using HEU fuel. At the same time, the IAEA was initiating efforts to update a similar list to better assist its member states. By combining the efforts of the two organizations, the joint IAEA–Academies meeting was able to attract a broad international community of experts to produce a list.

[10] Because of BWXT visitor restrictions, only committee members who were U.S. citizens (excluding U.S. citizens with dual citizenship) were allowed to participate in the tour.

[11] A note about research reactor naming convention: the names of research reactors can be written in all capital letters. In some cases, these names are acronyms, while in others they are a series of letters and numbers without acronyms. In this report, the capitalization of the name of the research reactor follows the reactor operator's use. For example, the MARIA reactor in Poland is capitalized (and is not an acronym) while the name of the Eole reactor in France is not.

with facility operators and gained a deeper understanding of and multiple perspectives on the issues surrounding the conversion of research reactors to LEU fuel. A full list of the committee's data-gathering sessions and site visits can be found in Appendix C.

The subject matter of the study touches on topics that are considered sensitive (i.e., nuclear security and terrorism). However, the entire report is publicly available, and the findings and recommendations are based on publicly available information. One organization provided unclassified, controlled-restricted information for this study through Freedom of Information Act exemptions approved by the Academies. This information was related to the U.S. government's pricing of HEU and LEU fuel and contributed to the committee's overall understanding of the various factors affecting fuel conversion. That said, none of the controlled-restricted information is included in this report.

Early in the study the committee chose a broad interpretation of its task statement as follows:

- The Task 1 list was generated using publicly available information only. A joint IAEA–Academies meeting and expert opinion obtained through public meetings and further supported through public documents provided important input.
- The Task 1 list of civilian reactors would include critical and subcritical assemblies, pulsed reactors, and steady-state reactors. A land-based reactor not connected to the grid (not providing electricity to the grid, for example) was the committee's working definition of "civilian research reactor"; therefore, the committee excluded propulsion reactors (e.g., spacecraft, icebreakers, or naval) in its definition. Research reactors with a dual use (i.e., civilian and military) were included in the Task 1 list; reactors with a sole military purpose were excluded because the statement of task clearly specifies the scope to include "civilian" reactors only.[12] See Chapter 2 and Appendix E for more details.
- Planned research reactors using HEU fuel were identified during numerous site visits and investigated through the IAEA's research

[12] The committee is aware of the Fissile Material Working Group's (FMWG's) recommendation to expand the scope of civilian research reactors to include propulsion and propulsion systems, but this was not consistent with the committee's interpretation of its statement of task. The FMWG recommendations for the 2016 Nuclear Security Summit are available at http://www.fmwg.org/FMWG_Results_We_Need_in_2016.pdf. P. 4: "Other civilian uses and non-weapons applications, including propulsion reactors and military research reactors, have been outside of the discussion. Though it will be politically difficult to establish consensus on elimination in all non-weapons applications, HEU minimization and elimination efforts cannot maximize security gains if the scope is not comprehensive."

reactor database. Other planned reactors were identified during consultations with experts.

- The "review of status" requested in Task 2 reviewed progress since the last major Academies study on this topic (NRC, 2009).
- The phrase "use of HEU in fuel for research reactors" from Task 3 included HEU fuel stored at civilian facilities (as defined above) such as fresh and spent fuel. This includes research reactors that shut down but have HEU fuel (fresh and/or spent) remaining on site. As such, the committee explored U.S. fuel return programs.
- The reference in Task 3 to "others" included programs throughout the world related to elimination of HEU fuel from research reactors.
- Conversion is a general term which can be defined as the changing of one type of fuel to another (i.e., different chemical composition or enrichment level) in a reactor. Throughout this report it typically refers to conversion of HEU-fueled reactors to LEU-fueled reactors. Exceptions will be clear from the context.

BACKGROUND

Proliferation concerns about the use of HEU in civilian applications have motivated national and international programs to replace HEU with LEU. Within the United States, the NNSA manages efforts to eliminate or minimize (where elimination is not possible) special nuclear materials[13] in civilian applications through the Office of Material Management and Minimization.[14] This office is organized into three major activities: material removal, reactor conversion, and material disposal.[15]

The history of the U.S. reactor conversion programs can be described by three periods and changes in management: 1978 to 2003, 2004 to 2014, and 2015 to the present. From 1978 to 2003, the Reduced Enrichment for Research and Test Reactors (RERTR) program was responsible for the initial conversion efforts for the U.S. government. In 2004, the Global Threat Reduction Initiative (GTRI) was established. From 2004 to 2014, conversions and related activities were led by GTRI's Convert Program. In part because of increased funding, the pace of conversions accelerated and

[13] Special nuclear material is defined by Title I of the Atomic Energy Act of 1954 as plutonium, uranium-233, or uranium enriched in the isotopes uranium-233 or uranium-235 (from USNRC website: http://www.nrc.gov/materials/sp-nucmaterials.html).

[14] See http://nnsa.energy.gov/aboutus/ourprograms/dnn/m3; M^3 was established in January 2015.

[15] For reasons noted above, the committee explored U.S. fuel return and removal programs, but it did not investigate the third pillar of the Global Threat Reduction Initiative (GTRI; secure) or the M^3 program (dispose).

the scope of the program expanded. The program also began to include shutdown research reactors in its progress metrics. The latter half of the GTRI Convert Program (2009, the date of its last domestic conversion, to 2014) was defined by an increased focus on a single basic formulation for very high-density LEU fuel and increased attention to conversion of non-U.S. reactors. Finally, in a January 2015 reorganization, GTRI became part of the new M^3 office, with the reactor conversion program remaining largely intact as the Office of Conversion (see Figure 1.1 for a time line of the U.S. conversion programs; further details on the M^3 reorganization can be found in Chapter 6). One of this committee's tasks is to assess progress of the conversion efforts over the past 5 years: the late-GTRI and M^3 eras.

Following many years of success in the conversion of both domestic- and foreign-owned civilian research reactors, the U.S. conversion program[16] has become increasingly focused on the challenges involved with the conversion of the high performance research reactors (HPRRs)[17] in the United States and Europe. Because many of these reactors are optimized for very high in-core/near-core neutron fluxes and have compact cores, they require the development of very high-density fuels (see Chapter 4 for more discussion of these fuels or Snelgrove et al., 1996; Van den Berghe and Lemoine, 2014). The U.S. conversion program requires that conversion will not significantly affect a reactor's safety, performance, or operations. These constraints present significant technical challenges, causing a major expansion of the time line for conversion of these reactors, now projected to be completed in 2035 (Bunn et al., 2014; DOE, 2014[18]), compared to the 2018 deadline projected in the NNSA's fiscal year (FY) 2009 budget request and discussed in the last Academies report (DOE, 2008[19]; NRC, 2009).

Several factors contribute to the urgency of optimizing the effectiveness of the M^3 Office of Conversion. The final Nuclear Security Summit will be held in 2016, thus ending focused international support on the goals aligned with those of the M^3 Office of Conversion and its other offices. The dates

[16] "The U.S. conversion program" refers to both the GTRI Convert Program and the M^3 Office of Conversion.

[17] High performance research reactors are, in the most general sense of the definition, reactors for which available fuels do not currently exist to support conversion without an effect on their performance (Roglans, written communication, September 2015). However, the use of "HPRR" in this report normally refers to research reactors that have compact cores and produce very high fluxes of neutrons.

[18] From the NNSA's FY 2015 budget request, p. 462: "By 2035, convert or verify the shutdown prior to conversion of approximately 200 HEU reactors and isotope production facilities."

[19] From the NNSA's FY 2009 budget request, p. 531:

> By 2018, convert to LEU 129 of 207 HEU reactors. (The IAEA identified 207 reactors designed to operate on HEU fuels. These reactors average 5 kg of HEU per reactor to operate. LEU fuel exists or is being developed which will allow 129 of these 207 reactors to be converted thus minimizing the use of HEU in civilian applications.)

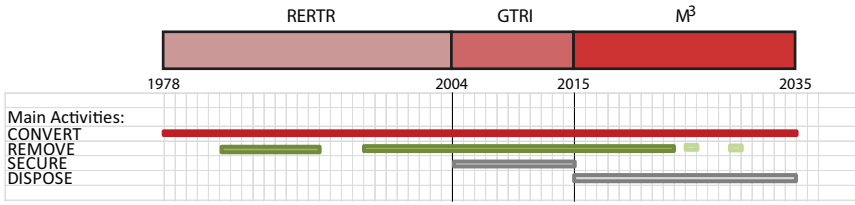

FIGURE 1.1 A time line of U.S. civilian research reactor conversion programs through the current projected end date of 2035. The Reduced Enrichment of Research and Test Reactor (RERTR) program was first established in 1978; the Global Threat Reduction Initiative (GTRI) replaced RERTR in 2004, and the Office of Material Management and Minimization (M^3) replaced GTRI in January 2015. This figure illustrates the changing mission of the programs; most recently, a change from GTRI's three main pillars of convert-remove-secure to M^3's focus on convert-remove-dispose (the management of securing civilian HEU has moved into another office within the National Nuclear Security Administration). The interrupted green bar shows a pause from 1993 to 1996 when the RERTR Program switched from reprocessing to spent fuel storage as a back-end solution because of a change in U.S. policy. The remove program is expected to end in 2022 with the conclusion of the Gap Removal program described in Chapter 6. Two exceptions to this end date have been granted: 2025 for Austria and 2029 for Japan. SOURCE: Landers (2014) and http://nnsa.energy.gov/aboutus/ourprograms/dnn/m3.

for conversion of the world's highest performance research reactors—which are, on average, more than 40 years old—are about two decades away (see Chapter 2), and the M^3 Office of Nuclear Material Removal is scheduled to end in 2022.[20] The last research reactor conversion in the United States was in 2009, and the rate of conversions worldwide has decreased (see Chapter 5), although permanent reactor shutdowns continue at a healthy pace. In addition, the M^3 Office of Conversion end date for converting the remaining research reactors that are not high performance has lengthened significantly, with a currently projected end date two decades away, comparable to the conversion dates for the HPRRs, although for different reasons.

[20] The U.S.-origin fuel return program is ending because nearly all of the fuel identified under this program (Training, Research, Isotopes, General Atomics [TRIGA], and Materials Test Reactors fuel) has either been returned or has been planned for return. This program is no longer an incentive for conversion. The Gap Materials Program is a broader-scoped program and continues to provide incentives for conversion through 2022 (and with some exceptions, beyond that date).

The committee investigated several questions as it addressed its task:

- If conversion to LEU fuel becomes possible at about the same time as the end of the operational lifetime of a reactor, then does it make sense to plan to convert that reactor if newly designed LEU-fueled reactors are being planned, constructed, or commissioned at the same time?
- What can be done to accelerate reactor conversions and minimize the quantities of the highest enriched civilian HEU fuel?
- What are other countries doing to accelerate conversion of HPRRs that require new fuel to be developed?

REPORT ROADMAP

The chapters of this report address the elements of the study charge. This first chapter provides background and an introduction to the study.

- Chapter 2 reviews the original and enduring motivations for the elimination of HEU from civilian applications, discusses the establishment of the definition of LEU, and provides an overview of the U.S. research reactor conversion program and its evolving scope over the years. The Task 1 list (civilian research and test reactors that operate using HEU fuel) is also provided in Chapter 2, with further discussion in Appendixes E (the synopsis of the IAEA-Academies meeting) and F (information collected by the committee from a wide variety of open sources on additional operating reactors that are considered outside the scope of this study). Chapter 2 also includes a review of civilian research and test reactor status over the past 5 years (Task 2).
- Chapter 3 discusses the purpose and performance requirements of the currently operating HPRRs and their continuing roles for science, engineering, and medical applications.
- Chapter 4 considers the technical obstacles to conversion of the remaining HEU-fueled civilian research reactors, primarily the HPRRs, including progress in developing high-density and very high-density fuels for the conversion of HPRRs and the consequent time line. In many cases, obstacles to reactor conversion are nontechnical.
- Chapter 5 reviews these nontechnical obstacles to conversion, paying particular attention to reactors in Russia, but also providing other examples to highlight both challenges and their potential solutions.

- Chapter 6 provides an assessment of the status and progress of the M^3 Office of Conversion, including the progress being made to eliminate worldwide use of HEU in fuel for civilian research and test reactors, and recommendations for how the program can improve its effectiveness.
- The concluding remarks in Chapter 7 highlight the continuing importance of HEU minimization and elimination in civilian reactors, underscore the challenges still to be tackled, and point to hopeful next steps for the M^3 Office of Conversion.
- Appendix C lists the committee's meetings and site visits during which it gathered information for this report. Appendix D provides a list of acronyms used throughout the report. Appendix G provides a glossary of terms.

2

Research Reactors Currently Using HEU Fuel

"No threat poses as grave a danger to our security and well-being as the potential use of nuclear weapons and materials by irresponsible states or terrorists," so warns the 2015 *National Security Strategy*[1] issued by the White House. Indeed, following the September 11, 2001, terrorist attacks, the imperative to prevent the spread of nuclear weapons has grown more urgent and essential, as has been recognized by both parties in the executive and legislative branches, as well as internationally.

One of the greatest barriers to implementing acts of nuclear terrorism and proliferation is obtaining enough weapon-usable fissile[2] material to make a weapon. Without sufficient plutonium, highly enriched uranium (HEU), or a small number of even harder to acquire isotopes, no bomb can be constructed. HEU, while requiring larger quantities to fabricate a weapon, is easier to work with and can be made to go supercritical with less sophisticated device designs. The threat was noted by former Los Alamos National Laboratory Director Harold Agnew, "For those who say building a nuclear weapon is easy, they are very wrong, but those who

[1] *National Security Strategy,* The White House, 2015, p. 11, and as of June 21, 2015, available at https://www.whitehouse.gov/sites/default/files/docs/2015_national_security_strategy.pdf.

[2] Fissile material is defined by the U.S Nuclear Regulatory Commission as: "A nuclide that is capable of undergoing fission after capturing low-energy thermal (slow) neutrons. Although sometimes used as a synonym for fissionable material, this term has acquired its more-restrictive interpretation with the limitation that the nuclide must be fissionable by thermal neutrons. With that interpretation, the three primary fissile materials are uranium-233, uranium-235, and plutonium-239" (see http://www.nrc.gov/reading-rm/basic-ref/glossary/fissile-material.html).

say building a crude device is very difficult are even more wrong."[3] Thus, the physical security and removal of HEU are of fundamental importance.

Two broad paths are available for preventing HEU from falling into the hands of would-be terrorists or proliferators. First, the material can be protected with perimeter security, access controls both physical and procedural, accountancy, and personnel and cyber security. Second, use of the material can be minimized or eliminated, with the number of facilities requiring it reduced, and it can be disposed of through downblending to lower enrichment levels.[4] The first approach—security—is by definition impermanent and potentially imperfect. The second approach—elimination—is preferred and more effective once it is completed.[5]

The Reduced Enrichment for Research and Test Reactors (RERTR), Global Threat Reduction Initiative (GTRI), and Material Management and Minimization (M^3) programs have focused on reducing the threat of nuclear terrorism by securing, converting, removing, and disposing of HEU and other nuclear weapon materials in civilian applications. The goal of the conversion program is to replace HEU with low enriched uranium (LEU) and thus greatly increase the difficulty of making a bomb (perhaps to the point that only states can do it).

Global civilian stocks of HEU total slightly more than 60 tons, while military stocks are 20 times as large (Mian and Glaser, 2015, p. 13). The true measure of merit, however, is the vulnerability of a single quantity of material sufficient to fabricate a nuclear device. HEU in civilian stocks is often less well protected than military stores. In particular, many civilian research reactor facilities are small and less well funded than military installations. According to the International Atomic Energy Agency (IAEA), "deficiencies remain, however, in the legal, administrative, and technical arrangements for controlling and protecting nuclear materials . . . in some countries" (IAEA, 2015, p. 3). Thus, the Department of Energy (DOE) nonproliferation programs such as GTRI and M^3 support removing HEU from such facilities.

[3] Quoted in U.S. Senate, Committee on Foreign Relations, "Dirty Bombs and Basement Nukes: The Terrorist Nuclear Threat," S. Hrg. 107-575, 107th Congress, 2nd Session, March 6, 2002 (Washington, DC: U.S. Government Printing Office, 2002), p. 22. This is also quoted in Bunn et al. (2011).

[4] "Downblending" reduces the enrichment level of HEU material by mixing the uranium alloy or compound with material of much lower ^{235}U enrichment (such as depleted uranium).

[5] Conversion to LEU fuel does not altogether eliminate the risk of proliferation, because material enriched below 20 percent can still be further enriched if capabilities are available.

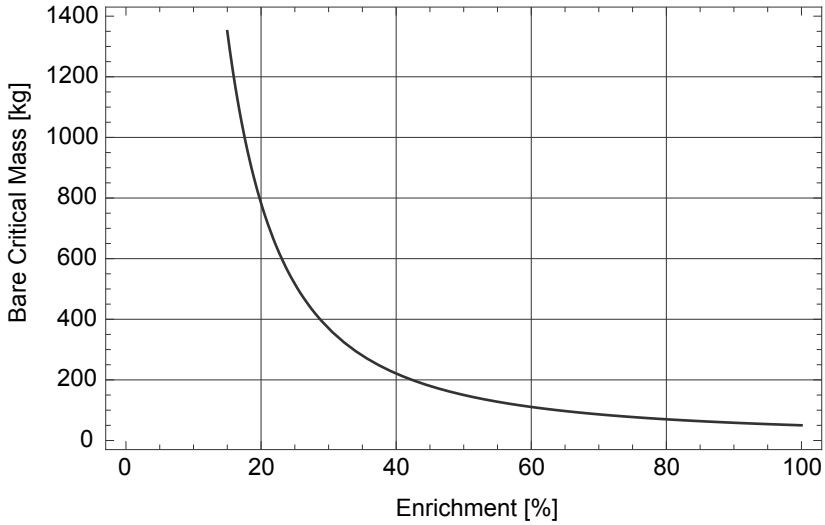

FIGURE 2.1 The bare critical mass of an unreflected sphere of uranium as a function of ^{235}U enrichment. Critical mass is an important indicator of the weapon-usability of uranium. It drops sharply as the enrichment level increases. The bare critical mass of W-HEU (greater than 90 percent ^{235}U) is about 50 kg. This amount is sufficient for a gun-type nuclear weapon. Much less material is needed for a nuclear weapon based on the implosion-type design (IAEA, 2001). SOURCE: Created from data within Glaser (2006).

DETERMINATION OF THE 20 PERCENT ENRICHMENT THRESHOLD FOR HEU

The critical mass of uranium, which is an important indicator of its weapon-usability, drops rapidly as the enrichment percent of uranium-235 (^{235}U) increases (see Figure 2.1). Weapon-grade HEU (W-HEU) is generally preferred for weapons applications,[6] but all material enriched to 20 percent and above is defined as HEU. This definition of LEU (enrichment below 20 percent but without using the term explicitly) was first introduced by the U.S. Atomic Energy Commission in 1954 (Brown, 2015). The formal definition of LEU was later also adopted by the IAEA, which classifies LEU as "indirect-use material" that cannot be used for "the manufacture of nuclear explosive devices without transmutation or further enrichment."[7]

[6] See, for example, http://ntiindex.org/behind-the-index/how-the-index-works/faqs/.

[7] IAEA Safeguards Glossary, p. 33. Available at https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf.

When the United States began to consider exporting research reactors to foreign countries, and first offered this opportunity at the 1955 Atoms for Peace Conference in Geneva, it also chose 20 percent as the enrichment level for use in the fuel of these reactors.[8] At the time, U.S. domestic research reactors were typically fueled with W-HEU; beginning in 1958, however, the United States also began export of HEU for foreign research reactors, effectively "converting" these reactors from LEU to HEU, mainly to improve their performance.

The proliferation (and security) risks directly associated with civilian research reactor fuel fall into two main categories: diversion or theft of weapon-usable HEU, which could be extracted from the fresh (or spent) fuel[9] and used for weapon purposes; and production of plutonium, which could be separated from the irradiated fuel of the research reactor. Identifying an enrichment level that balances overall proliferation concerns of both materials was recognized as important in the earliest years of the conversion program (Travelli, 1978, p. 3):

> The proliferation resistance of nuclear fuels used in research and test reactors can be considerably improved by reducing their uranium enrichment to a value less than 20 percent, but significantly greater than natural to avoid excessive plutonium production.

The choice of 20 percent as a target enrichment for research reactors is not obvious, because plutonium production within the fuel itself increases as the fuel enrichment decreases, and there is no sharp boundary in Figure 2.1 to determine a threshold for uranium enrichment. For example, a 40-MW natural-uranium-fueled reactor makes about 8 kg of plutonium per year, enough for at least one nuclear weapon, while its (fresh) uranium fuel is of very little concern. At the other extreme, a similar 40-MW reactor fueled with W-HEU makes almost no plutonium (less than 100 g per year), but

[8] At the first Atoms for Peace Conference held in Geneva in 1955, Alvin Weinberg reported that he had "just received information from my country that sample UO_2-aluminum 20 percent enriched fuel elements of the type which will be available to foreign countries have now been tested both in the LITR [low-intensity testing reactor] and in the MTR [materials test reactor]" (Session 9A, Vol. II, August 12, 1955, p. 430).

[9] The HEU fuel used in research reactors poses different levels of threat. For example, fresh or lightly irradiated HEU fuel poses a greater threat than spent, highly irradiated fuel, because the radioactivity from spent fuel provides an additional barrier to theft or removal and recovery of the enriched uranium requires chemical separation. A good example of research reactor facilities that pose such a risk are critical and subcritical assemblies that store a large amount of lightly irradiated HEU (hundreds to thousands of kilograms).

requires about 30 kg of fresh HEU fuel per year.[10] More detailed analyses confirm that there is indeed a region of intermediate enrichment, where the overall "value" for weapon use of the materials involved in the operation of a research reactor is lowest; an enrichment level of about 20 percent minimizes the attractiveness of both the uranium and the plutonium routes to a weapon. If use of LEU is preferred for reactor conversion, then an enrichment level close to this limit (e.g., 19.75 percent) both optimizes reactor performance and minimizes proliferation risks associated with the fuel.[11] It is worth noting that DOE's scale of material attractiveness for nuclear weapons material assigns a lower "attractiveness level" to material that is less than 50 percent enriched in ^{235}U (compared to material above this threshold).[12]

In some circumstances, there may be concerns that a proliferator could enrich a batch of LEU research reactor fuel to obtain weapon-grade material, for example, enriching fuel material from 20 percent to 90 percent ^{235}U. A reactor using 20 percent enriched uranium fuel requires about twice as much fuel as a similar reactor using 45 percent enriched uranium. For a potential proliferator, this corresponds to a respective increase in available feedstock for enrichment by a factor of two. About three times more separative work[13] is needed to enrich a given amount of fuel from 20 to 90 percent enrichment compared to the separative work needed to enrich one-half that amount of fuel from 45 to 90 percent. In both cases, a proliferator with an existing enrichment capability or access to enrichment capabilities could process the available material in a very short period of time, even in a small (and perhaps undeclared) enrichment plant (Glaser, 2006).

Today, there is a broad consensus internationally that 20 percent enrichment is a sound choice for the ultimate conversion target. A stepwise approach to this target was considered in the early days of the RERTR Program, reducing the fuel enrichment level from 90 percent to an intermediate

[10] The IAEA (2001, p. 23, Table II) defines 25 kg of HEU and 8 kg of plutonium to be "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded."

[11] Other technical attributes associated with optimal bomb design are considered in determining the 20 percent factor and can be further explored in Glaser (2006). For example, as the enrichment level drops, not only the critical mass but also the neutron background (dominated by the presence of ^{238}U) increases, which further complicates the use of the material in a gun-assembly device.

[12] For more information on DOE attractiveness levels, see p. B-1 of http://www.energy.gov/sites/prod/files/2013/09/f2/DOE-STD-1194-2011_CN2.pdf.

[13] Separative work unit, abbreviated as SWU, is the standard measure of the effort required to separate isotopes of uranium (^{235}U and ^{238}U) during an enrichment process in nuclear facilities; 1 SWU is equivalent to 1 kg of separative work. From http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Separative_work_unit_(SWU).

level before finally reaching 20 percent.[14] Both the U.S. RERTR Program and the International Nuclear Fuel Cycle Evaluation (INFCE, 1978–1980) considered 45 percent as an interim step toward reactor conversion to 20 percent if an adequate fuel for a direct conversion to 20 percent were not available. For reactors using U.S.-origin HEU fuel, this option was almost never used (the original Forschungsreaktor Munich [FRM] in Germany is one exception), and when high-density silicide fuels became available in the late 1980s, the option was no longer considered necessary or worthwhile, given the (unfortunately overly optimistic) prospect of timely conversion of all HEU-fueled research reactors.

The Soviet Union, too, used W-HEU in its reactors but chose to limit the enrichment level of reactors exported to other countries to 80 percent. In 1980, following the INFCE effort, the Soviet Union quietly established a conversion program (similar to the U.S. RERTR Program) and gradually started converting foreign reactors to 36 percent (Arkhangelsky, 1997). By the late 1980s the Soviet Union also adopted the 20 percent conversion target for Soviet-supplied research reactors but had paused its LEU fuel development (Travelli, 1992; Arkhangelsky, 1997). Currently, Russia uses the below 20 percent LEU enrichment limit for its new generation of icebreakers and floating nuclear power plants.[15] Like the United States, however, Russia continues to supply W-HEU to some customers. Additionally, Russia has recently restarted HEU production on a small scale (IPFM, 2013).

U.S. PROGRAMS TO ADDRESS THREAT OF CIVILIAN USE OF HEU

The U.S. effort to convert civilian research reactors using HEU fuel has benefited from sustained bipartisan support over several decades from both the White House and Congress. President George H. W. Bush signed the Nunn-Lugar legislation in 1991, framing nuclear security cooperation with Russia in the post-Soviet era. President Bill Clinton established the nuclear security programmatic agenda, including expanded cooperation with Russia. President George W. Bush focused conversion efforts within the U.S. government when he established the GTRI in 2004 and supported them with significant budget increases. Most recently, President Barack Obama used the Nuclear Security Summits to accelerate conversion and threat material removal efforts and to instill a sense of personal responsibility among heads of state and their governments for the security of fissile

[14] See, for example, extensive analyses of both 20 percent and 45 percent cases in *Research Reactor Core Conversion from the Use of Highly Enriched Uranium to the Use of Low Enriched Uranium Fuels Guidebook,* IAEA-TECDOC-233, International Atomic Energy Agency, Vienna, 1980.

[15] See http://www.world-nuclear.org/info/Non-Power-Nuclear-Applications/Transport/Nuclear-Powered-Ships/.

material under their control. This national priority has also been reflected in the large congressional appropriations for the GTRI and M^3 programs in recent years.[16] This sustained support resulted in a nearly 40-year U.S. effort on research reactor conversion, noted in Chapter 1 (see Figure 1.1).

The scope of the research reactor conversion program has changed over the years. Originally, the RERTR Program included only U.S.-supplied foreign civilian research reactors, with a focus on reducing HEU exports to zero (Travelli, 1978). By the mid-1980s the scope expanded to include U.S. domestic reactors, resulting in a total of 70 in-scope reactors (about 28 domestic reactors [Staples, 2013] and 42 U.S.-supplied foreign reactors).[17] As the United States was launching the RERTR Program in 1978, the IAEA in parallel hosted the INFCE.[18] The INFCE study found that the "proliferation resistance [of research reactors] can be increased by . . . enrichment reduction preferably to 20 percent or less" (INFCE, 1980, p. 43). As a result of the INFCE study and the concurrent U.S. initiative, several other Western countries joined the conversion effort with independent research and development efforts, including major users of U.S.-origin research reactors such as Japan, France, and Germany.

With the launch of the GTRI Convert Program in 2004, the scope of the conversion effort broadened substantially. Given new concerns about nuclear terrorism, the conversion effort included research reactors using HEU fuel that were neither U.S. nor Russian designed. The Convert Program also placed a stronger focus on U.S. domestic reactors and began to broaden its attention to the conversion of critical assemblies in the United States and elsewhere. Other organizations also developed lists of HEU-fueled research reactors, as discussed below. By 2014 a total of 200 operating HEU-fueled research reactors were considered within the scope of the GTRI Convert Program.[19]

Between 2004 and 2009, the conversion goals of the GTRI Convert Program expanded (with lengthened completion schedules as shown in

[16] Chris Landers, written communication, dated August 5, 2015, provides budget numbers for the past 5 years.

[17] See, for example, Matos (1996) and presentations by A. Travelli on "The RERTR Program: A Status Report" at multiple International Meeting(s) on Reduced Enrichment for Research and Test Reactors: 1989–1993, and James (Jim) Matos, written communication, August 24, 2015.

[18] The IAEA has no official policy on HEU minimization, but it strongly and actively supports all HEU minimization activities. The fuel supply for new research reactors is approved by the Board of Governors of the IAEA (under what is called a Project and Supply Agreement). Board of Governors meetings include many Member States (including the United States) who are likely to strongly stand against an approval of any supply of HEU fuel through the IAEA.

[19] See, for example, lists supplied by GTRI to the committee in 2014, and within the DOE/NNSA FY 2013 Budget Request (DOE, 2012, p. 465).

TABLE 2.1 Evolution of Scope and Deadlines to Complete the Conversion of GTRI-Targeted Research Reactors

Year	Number of Reactors to Be Converted or Shut Down, Within GTRI Scope	Deadline for Conversion	Total Number of HEU-Fueled Reactors Worldwide[a]	As Reported in NNSA Budget Justification Documents (fiscal year shown)
2004	Not reported	2013	Not reported	FY 2008
2005	105	2014	Not reported	FY 2008
2006	106	2014	Not reported	FY 2008
2007	129	2018	207	FY 2011
2008	129	2018	207	FY 2011
2009	129	2018	207	FY 2011
2010	200	2020	Not reported	FY 2012
2011	200	2020	Not reported	FY 2012
2012	200	2025	Not reported	FY 2014
2013	200	2030	Not reported	FY 2014
2014	200	2035	Not reported	FY 2015

[a] Total number of HEU-fueled reactors worldwide includes some defense reactors.
SOURCE: Data collected from NNSA budget justification documents; fiscal year (FY) shown in table (DOE, 2007, 2010, 2011, 2013a, 2014).

Table 2.1 and Figure 2.2) in the same manner as its scope. Progress in conversions is discussed in Chapter 6.

LIST OF CIVILIAN RESEARCH AND TEST REACTORS THAT OPERATE USING HEU FUEL

An IAEA technical meeting in January 2006 was the first international effort to compile an official list of HEU-fueled research reactors worldwide. The Academies also made an effort to compile a list of HEU-fueled research reactors as part of the 2009 study on *Medical Isotope Production Without Highly Enriched Uranium* (NRC, 2009). The list identified the total number of reactors by country and by category (operational and conversion status). Among the operating HEU-fueled reactors, the report identified 125 (civilian) reactors in scope and 78 out of scope of the GTRI Convert Program.[20] The committee, however, recommended that critical facilities,

[20] The out-of-scope reactors on the list had defense-related missions, unique fuels, special-purpose designs, or were located in countries that did not at the time of the report cooperate fully with the United States on reactor conversion programs (NRC, 2009, p. 154).

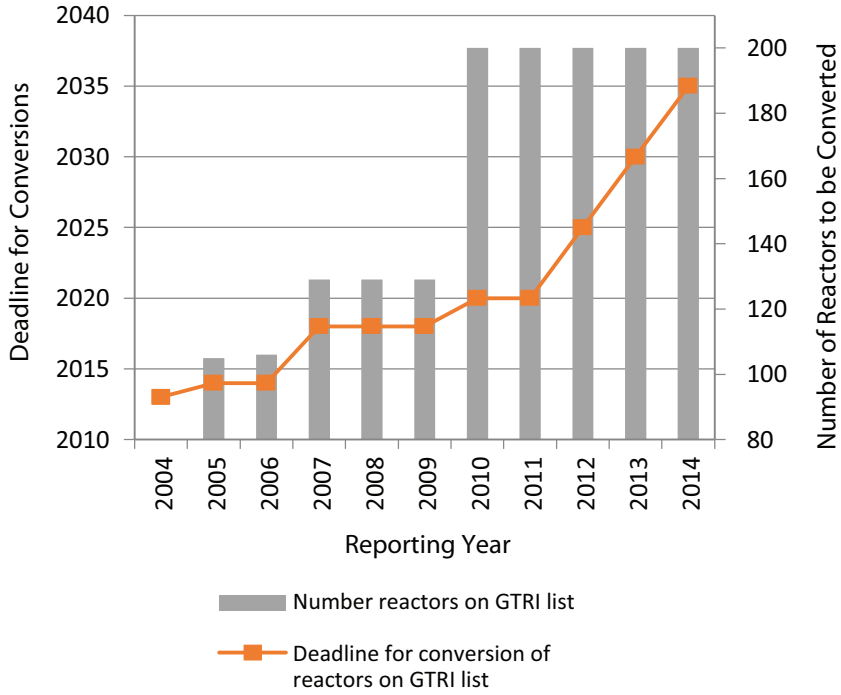

FIGURE 2.2 The expanding scope of the GTRI reactor conversions (gray columns) and the lengthening time line for conversion completion (orange line) by year reported in budget requests to the U.S. Congress, from 2004 to 2014. In 2005, it was reported that by 2014 all of the 105 reactors on the GTRI list would be converted or shut down. By 2014, the deadline had moved to 2035 and the list had expanded to 200. Note the significant increase in deadline between reporting years 2011 and 2014. SOURCE: Created from data collected from NNSA budget justification documents; fiscal year (FY) shown in Table 2.1 (DOE, 2007, 2010, 2011, 2013a, 2014).

pulsed reactors, and defense-oriented reactors (excluding naval propulsion reactors) "should be investigated to determine if it is feasible to convert them to LEU; if so, they should become in-scope for the [GTRI] program" (NRC, 2009, p. 162).

Task 1 of the charge for the present committee is to provide "a list of *civilian* research and test reactors that operate using HEU fuel" (emphasis added). As shown in Table 2.1 and the discussion above, the lists of civilian research reactors using HEU fuel have evolved over the years based on changing scope, reactor missions (i.e., civilian, military), and operating status (i.e., operational, decommissioned). To address this task, the com-

mittee carefully reviewed publicly available information on the status of HEU-fueled research reactors using a range of different sources.[21] As part of the effort to identify the civilian reactors operating on HEU fuel, the committee collected information from a wide variety of open sources on additional operating reactors that are considered outside the scope of this study. These are listed in Appendix F for completeness and to allow for cross-comparison with other publicly available lists.

The committee organized a joint IAEA–Academies meeting in July 2015 at the IAEA headquarters in Vienna, Austria, to arrive at an authoritative list of HEU-fueled civilian research and test reactors to address Task 1 and to reconcile the draft list assembled by the committee with the information available to the IAEA, which maintains a Research Reactor Database (RRDB).[22] The meeting brought together IAEA experts, committee members, and research reactor experts from across the world. Appendix E contains a meeting synopsis, the list of civilian research reactors currently operating with HEU fuel established by the meeting participants, and a participant list.

The committee carefully reviewed the list produced from this IAEA-Academies meeting and decided to adopt it with the addition of two reactors: the Jules Horowitz Reactor (JHR) in France and the Crystal (also spelled "Kristal") critical assembly in Belarus. The JHR reactor is under construction and does not yet have fuel on site; hence, it did not meet the criteria for inclusion on the joint IAEA–Academies list (see Appendix E, Table E.1 for the list of criteria). Because it is anticipated to use HEU fuel until a high-density LEU fuel is available,[23] this reactor has been added to the committee's list. The Crystal critical assembly in Belarus operates with an HEU core (Sikorin et al., 2013). As noted in Appendix E, two of the research reactors that had appeared on the meeting's final list have since shut down with HEU fuel removed: the SLOWPOKE research reactor in Jamaica and the AGN-211-P in Switzerland.[24] They do not appear in the lists found in Tables 2.2 or E.1.

Table 2.2 provides a list of 74 civilian research reactors currently using or under construction and planning to use HEU fuel. The committee

[21] For example, the committee used lists supplied by GTRI to the committee in 2015 (Chamberlin, 2015); existing lists from the International Panel on Fissile Materials (IPFM), the Nuclear Threat Initiative (NTI), and the IAEA research reactor database; and lists reported by researchers at international conferences (Hustveit and Reistad, 2012).

[22] See https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx.

[23] JHR will start up with LEU fuel but will then use HEU fuel so that it can meet operational requirements.

[24] See announcements from the NNSA for the Jamaican SLOWPOKE reactor (http://nnsa.energy.gov/mediaroom/pressreleases/nnsa-removes-u.s.-origin-heu-jamaica-makes-caribbean-heu-free) and the Swiss AGN-211-P (http://nnsa.energy.gov/mediaroom/pressreleases/last-heu-removed-switzerland-under-nnsa-collaboration).

TABLE 2.2 The 74 Currently Operating Research Reactors Using HEU Fuel, Alphabetical by Country (and by Reactor Name Within Each Country)

	Country	Reactor	Reactor Type
1	Belarus	Crystal/Kristal	Critical Assembly
2	Belarus	Hyacinth/Giacint	Critical Assembly
3	Belarus	Yalina B	Subcritical Assembly
4	Belgium	BR2	Steady State
5	Belgium	VENUS	Fast Critical Assembly
6	Canada	SLOWPOKE AB	Steady State
7	Canada	SLOWPOKE SK	Steady State
8	China	CEFR	Prototype Fast Power
9	China	MNSR-IAE	Steady State
10	China	MNSR-SZ	Steady State
11	China	Zero Power Fast	Fast Critical Assembly
12	DPRK	IRT-DPRK	Steady State
13	DPRK	IRT-DPRK CA	Critical Assembly
14	France[a]	Jules Horowitz Reactor (JHR)	Steady State (under construction)
15	France	Masurca	Fast Critical Assembly
16	France	Minerve	Critical Assembly
17	France	Neutronographie Phénix	Critical Assembly
18	France	Orphée	Steady State
19	France	RHF	Steady State
20	Germany	FRM-II	Steady State
21	Ghana	GHARR-1 (MNSR)	Steady State
22	Iran	ENTC (MNSR)	Steady State
23	Israel	IRR-1	Steady State
24	Italy	TAPIRO	Steady State
25	Japan	FCA	Fast Critical Assembly
26	Japan	KUCA (Dry Cores)	Critical Assembly
27	Japan	KUCA (Wet Core)	Critical Assembly
28	Japan	UTR Kinki	Steady State
29	Kazakhstan	IGR	Pulsed Reactor
30	Kazakhstan	IVG-1M	Steady State
31	Kazakhstan	WWR-K	Steady State
32	Nigeria	NIRR-1 (MNSR)	Steady State
33	Pakistan	PARR-2 (MNSR)	Steady State

continued

TABLE 2.2 Continued

	Country	Reactor	Reactor Type
34	Russia	AKSAMIT	Critical Assembly
35	Russia	ASTRA	Critical Assembly
36	Russia	BARS-4	Pulsed Reactor
37	Russia	BARS-6	Pulsed Reactor
38	Russia	BFS-1	Fast Critical Assembly
39	Russia	BFS-2	Fast Critical Assembly
40	Russia	BOR-60	Fast Reactor
41	Russia	CA MIR.M1	Critical Assembly
42	Russia	DELTA	Critical Assembly
43	Russia	EFIR-2M	Critical Assembly
44	Russia	FM PIK	Critical Assembly
45	Russia	FS-1M	Critical Assembly
46	Russia	GIDRA	Pulsed Reactor
47	Russia	IR-8	Steady State
48	Russia	IRT-MEPhI	Steady State
49	Russia	IRT-T	Steady State
50	Russia	IVV-2M	Steady State
51	Russia	K-1	Critical Assembly
52	Russia	KVANT	Critical Assembly
53	Russia	MAKET	Critical Assembly
54	Russia	MIR.M1	Steady State
55	Russia	NARCISS-M2	Critical Assembly
56	Russia	OR	Steady State
57	Russia	PIK	Steady State
58	Russia	RBT-10/2	Steady State
59	Russia	RBT-6	Steady State
60	Russia	SM-3	Steady State
61	Russia	SM-3 CA	Critical Assembly
62	Russia	ST-1125	Critical Assembly
63	Russia	ST-659	Critical Assembly
64	Russia	WWR-M	Steady State
65	Russia	WWR-Ts	Steady State
66	Syria	SRR-1 (MNSR)	Steady State
67	United States	ATR	Steady State

TABLE 2.2 Continued

	Country	Reactor	Reactor Type
68	United States	ATR-C	Critical Assembly
69	United States	GE-NTR	Steady State
70	United States	HFIR	Steady State
71	United States	MITR-II	Steady State
72	United States	MURR	Steady State
73	United States	NBSR	Steady State
74	United States	TREAT	Steady State

[a] JHR is currently under construction and will use HEU fuel to meet operational requirements until a high-density LEU fuel is available.
SOURCE: Modified from TABLE E.2, "Civilian Reactor Facilities Operating on HEU Fuel, Alphabetical by Country," developed by participants at the joint IAEA–Academies meeting in Vienna, Austria, July 2015.

included critical facilities and pulsed reactors but excluded defense-oriented reactors specifically because the statement of task directed it to focus on *civilian* research reactors.

Figures 2.3a and b highlight two distributions of these remaining reactors: Figure 2.3a shows the distribution of reactors by country, and Figure 2.3b shows the approximate annual consumption of HEU by reactor (Figure 2.3b presents an estimation of annual HEU consumption; actual consumption depends on factors including standard [not maximum] operating power). These charts illustrate the countries with the most research reactors (Russia, United States, and France) and the highest-consumption reactors (ATR, HFIR, and MIR.M1). In Figure 2.3b, the top seven reactors consume 80 percent of the total annual civilian HEU for research reactors (these reactors represent 10 percent of the total in Table 2.2). Within this category, three of the top seven are in the United States, three are in Europe, and one is in Russia. Figure 2.3b does not highlight critical assemblies, which have no annual consumption, but may house significant amounts of lightly irradiated HEU fuel, still posing a security and/or proliferation threat.

The list of reactors in Table 2.2 represents a snapshot in time. The status of reactors can change. Besides conversion or shutdown (and decommissioning), some facilities may temporarily shut down, for example, to undergo maintenance or facility upgrades, with the intent of restarting. In addition, the mission of some research reactors can evolve; occasionally, the mission of a reactor shifts from military to civilian applications and vice versa. As a result, it is important to periodically review and update the list. The fluidity of the list reinforces a recommendation of the 2009 Academies

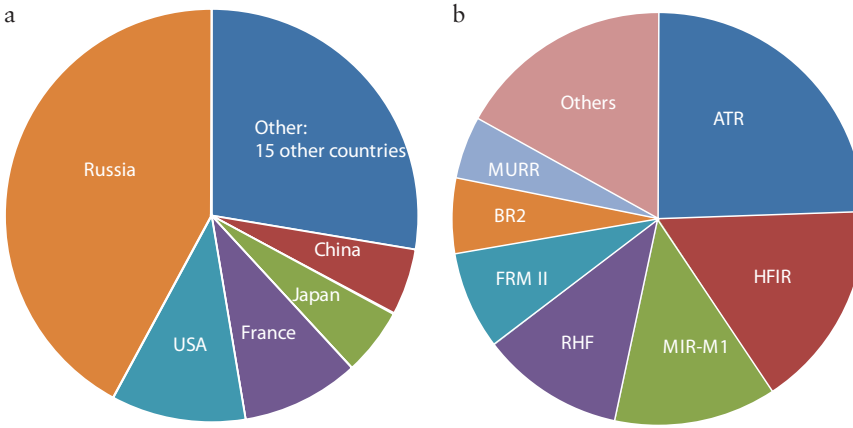

FIGURE 2.3 Distributions of civilian research reactors currently using HEU fuel (a) by country (see Table 2.2) and (b) by approximate HEU annual consumption. Figure 2.3a identifies countries with four or more reactors; 15 countries have three or fewer research reactors currently operating with HEU fuel. In Figure 2.3b, three of the top seven are in the United States (ATR with 120 kg, HFIR with 80 kg, and MURR with 24 kg approximate annual consumption), three are in Europe (RHF/ILL with 55 kg, FRM-II with 38 kg, and BR2 with 29 kg approximate annual consumption), and one is in Russia (MIR.M1 with 62 kg annual consumption). SOURCE: Table 2.2 and Meyer (2006).

study that "DOE-NNSA [National Nuclear Security Administration], in cooperation with IAEA, make an effort to maintain an up-to-date and comprehensive database of the research and test reactors of the world, including large pulse reactors, critical facilities, and reactors with defense-oriented mission"(NRC, 2009, p. 162).

PLANS FOR FUTURE RESEARCH REACTORS

The IAEA research reactor database (RRDB) lists 11 planned research reactors. To the committee's knowledge, none of these reactors will use HEU fuel (see Table 2.3). The Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA) in Belgium and the multipurpose sodium-cooled fast neutron research reactor (MBIR) in Russia will be fast reactors that use mixed oxide (MOX) fuel.[25] The PALLAS reactor in Petten,

[25] Plutonium can be recovered from spent nuclear fuel via reprocessing. Fuel made from this recovered plutonium is "mixed oxide," or MOX, fuel. MOX fuel provides a small percentage of the nuclear fuel used in nuclear power reactors today (see http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Mixed-Oxide-Fuel-MOX/).

TABLE 2.3 Planned Civilian Research and Test Reactors

Country	Facility Name	Type	Thermal Power (kW)
Argentina	RA-10	POOL	30,000
Belgium	MYRRHA	FAST	85,000
Brazil	RMB	POOL	30,000
China	TFHR Thorium Pebble Bed	EXPERIMENTAL	2,000
China	TMSR Thorium Molten Salt	EXPERIMENTAL	2,000
Jordan	Jordanian Research and Test Reactor (JRTR)	POOL	5,000[a]
Republic of Korea	KJRR	POOL	15,000
Netherlands	PALLAS	POOL	[b]
Russia	MBIR	FAST, POWER	150,000
Saudi Arabia	RR-1	POOL	30
Ukraine	Multipurpose RR	POOL	20,000
United States	HT3R[c]	He COOLED	25,000
Vietnam	Multipurpose Research Reactor	POOL, IRT	15,000

[a] The JRTR nominal power will be 5,000 kW(thermal) but is expected to be upgradable to 10,000 kW. See http://www.cab.cnea.gov.ar/igorr2014/images/presentations/17thNovMonday/CondorRoom/2ndBlock/03AymanHAWARI.pdf.
[b] Thermal power was not specified in the IAEA Research Reactor Database (RRDB).
[c] The HT^{3}R High-Temperature Teaching and Test Reactor, at the University of Texas has been put on hold: http://www.utpb.edu/research-grants/ht3r.
SOURCE: Modified from IAEA RRDB (accessed August 27, 2015).

Netherlands, will replace the High Flux Reactor (HFR) and will use LEU fuel. Not shown in the list are the JHR under construction in France and the PIK reactor in Russia. As discussed previously in this report, the JHR is expected to start full operations with HEU fuel and plans to convert to LEU once a suitable fuel is available. The PIK reactor in Russia recently began operations at 100 W. Both reactors are included in Table 2.2 (which lists only operational reactors or those under construction that currently use or plan to use HEU fuel).

FINDINGS

Finding 1: Periodic meetings that bring together informed scientists and engineers from countries that employ research reactors are useful for the updating of the civilian HEU-fueled research reactor list.

Finding 2: Although the committee addressed its Task 1 requirement, which is limited to civilian research and test reactors, it supports the 2009 National Academies of Sciences, Engineering, and Medicine guidance to retain a larger list of reactors using HEU fuel that could potentially be converted to LEU fuel.

3

Research Reactors and Their Uses

This chapter provides background information on research reactors, including the history and performance of research reactors, discusses alternative sources of neutrons, and provides an overview of general uses of civilian research and test reactors, including specific uses of high performance research reactors (HPRRs). It concludes by discussing the future role of research reactors in supporting science, engineering, and medicine.

HISTORY OF RESEARCH REACTOR DEVELOPMENT

The first self-sustaining nuclear reactor, Chicago Pile-1 (CP-1), was assembled in 1942, producing a maximum power of 200 W. Within 20 years, the design of research reactors had progressed to the point that the average neutron flux (number of neutrons per unit area, per second) had increased by nearly nine orders of magnitude (see Figure 3.1). The availability of highly enriched uranium (HEU) fuel allowed for much of this increase. Figure 3.1 shows how the thermal neutron[1] flux in research reactors has evolved over time.

The trend is clear: A flux of thermal neutrons in the reactor core of roughly 10^{15} neutrons per square centimeter per second (n/cm^2-s) was achieved in the mid-1960s and has not been greatly exceeded since (see Table 3.1 for the listing of maximum flux for the highest-performance existing research reactors). This limit arises because the amount of cooling required increases with the flux, or power density, of the reactor. Beyond

[1] Thermal neutrons have an average velocity of about 2 km/s.

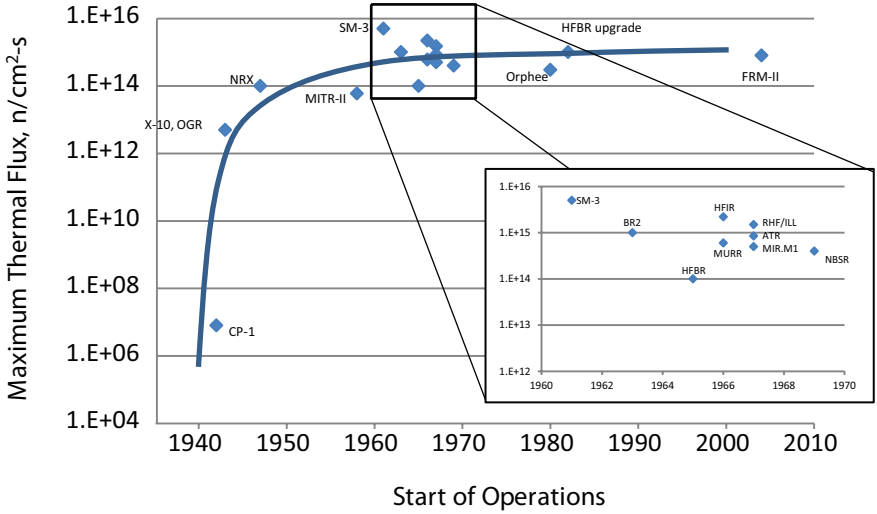

FIGURE 3.1 Evolution of neutron flux in a research reactor over time. For early neutron sources and for the named research reactors, the vertical axis gives the approximate maximum thermal neutron flux in or close to the reactor core, while the horizontal axis is the year in which the facility first produced neutrons. SOURCE: Based on data from multiple sources; see Table 3.1.

a certain power density (the level of which depends on the reactor design), supplying the required level of cooling may not be possible. The high neutron flux produced by the reactors shown in Figure 3.1 allows for execution of many critical missions.

USES OF RESEARCH AND TEST REACTORS

Research reactors are indispensable tools in the education and training of reactor operators and nuclear engineers, basic and applied research in a wide range of scientific areas, and the production of scientifically and technologically important materials, such as radioisotopes. Such reactors are also used for testing new types of nuclear fuel and studying the radiation resistance of new materials and electronic devices. A technical report published by the International Atomic Energy Agency (IAEA, 2014) describes in detail the typical uses of research reactors and outlines the necessary technical criteria required for each application. The IAEA report categorizes the uses of research reactors into three main areas—training and education, irradiation applications, and extracted beam applications; the same groupings are followed here.

Training and Education

Research reactors are well suited for training operators of nuclear power plants, because they provide hands-on access to reactor systems that are effectively hidden in power reactors and the capability to simulate abnormal conditions for training purposes (which cannot be done at power plants [Agasie et al., 2011]). Any functioning research reactor, irrespective of its operating power, can also be used for broader training and education, including formal education of nuclear engineers and radiological technicians, as well as educational events involving other students and the general public.

Irradiation Applications

Irradiation applications of research reactors generally involve inserting specimens into the reactor (in either the in-core or near-core regions where the neutron flux is highest) to induce radioactivity, produce isotopes, or induce radiation damage.

Research Reactors for Transmutation Applications

Transmutation is the conversion of elements and isotopes into other elements or isotopes through reactions in the nucleus.[2] One useful application of nuclear transmutation involves the creation of dopants within a semiconductor. For example, neutron irradiation of pure silicon transmutes silicon-30 (^{30}Si), which constitutes roughly 3 percent of natural silicon, to the dopant phosphorus, ^{31}P, thereby producing an n-type semiconductor. This neutron transmutation doping (NTD) technology is valued because it provides extremely uniform doping that leads to superior performance of silicon in high-power electronic applications. Medium-flux reactors are well suited to this application, because they achieve the required very uniform and precise irradiation levels in a reasonable length of time. These constraints limit the application of NTD to a few research reactors that have been optimized for this application.

At low power levels, research reactors may be used for analytic techniques such as neutron activation analysis (NAA), wherein irradiation produces radionuclides characteristic of the elements in a sample. These radionuclides often decay by emitting gamma rays with characteristic energy and intensity. Analysis of these gamma rays allows the identity and quantity of particular elements in a specimen to be assessed. The IAEA

[2] Adsorption of a neutron causes a change in atomic number, producing another element. Fission (a splitting of the nucleus) produces two nuclides having different atomic numbers and masses from the original.

estimates that NAA is the most widely used application of research reactors after education and training. Customers for NAA include industries such as mining or agriculture (e.g., for determination of trace elements in geologic matrices or the distribution of agricultural chemicals in soils), government agencies (e.g., for forensics), medical centers (e.g., for testing doses of pharmaceutical products), and research institutions (e.g., for determination of the origin of archeological specimens such as pottery). Although not all elements can be analyzed using NAA, the method has the advantage of performing compositional analysis without chemically altering a specimen. In addition, NAA is largely independent of matrix effects, is suitable for materials that are difficult to dissolve, and is relatively insensitive to sample contamination.

Radioisotopes have a wide range of applications in nuclear medicine, industry, and research. Production of these isotopes in research reactors is based on neutron absorption by a target material introduced into the reactor core. In general, the quantity of an isotope that can be produced in a given amount of time will increase as the neutron flux increases. Although the production rate may be linearly proportional to the neutron flux in some cases, for isotopes that require multiple successive neutron capture events the production rate is proportional to higher powers of the flux. More than 80 percent of diagnostic medical procedures utilize technetium-99m, which is a decay product of molybdenum-99 (^{99}Mo) (OECD, 2015). Many research reactors produce or are planning to produce this radioisotope for commercial purposes. However, other medically useful isotopes are also produced in research reactors, and new diagnostic procedures involving radioisotopes continue to be developed. Because the isotopes decay with half-lives measured in hours or days, they must be produced quickly and in large quantities, so a reactor with high flux (on the order of 10^{14} n/cm^2-s) is needed to produce them. For example, the University of Missouri Research Reactor (MURR) and the Belgian Reactor-2 (BR2) are each able to produce a wide variety of radioisotopes (Butler and Foyto, 2015; Ponsard and Blowfield, 2010).

Only the highest-flux reactors (with flux on the order of 10^{15} n/cm^2-s) can generate significant quantities of some isotopes such as Californium-252 (^{252}Cf) (used for neutron radiography and the start-up of nuclear reactors, for example) because capture of several neutrons in very rapid succession is required and these events are relatively rare. The High Flux Isotope Reactor (HFIR) in the United States and the SM-3 reactor in Russia are the only two research reactors in the world currently producing ^{252}Cf.

The primary alternative to research reactors for transmutation applications is the use of accelerators, either for direct irradiation with charged particles or for generation of neutrons. Accelerators are in widespread use at hospitals around the world for medical isotope production. On-site pro-

duction facilities are necessary for the shortest-lived isotopes, and direct use of charged-particle accelerators are generally more effective for producing neutron-deficient isotopes such as fluorine-18 (^{18}F).

The rate at which transmutation products can be produced increases as the magnitude of the flux increases. An equally important parameter for most applications is the volume over which such a uniform neutron flux is achievable. While accelerator-based systems can be developed to provide reasonable irradiation volumes, they often suffer from substantial flux gradients. For accelerator-based isotope production applications, the flux gradient results in reduced throughput; for accelerator-based transmutation doping applications, such gradients are counter to a primary advantage of the transmutation doping approach—uniform production of dopants.

Research Reactors for Materials Testing

An important class of research reactors, often referred to as Materials Test Reactors (MTRs), is used to test the behavior of structural materials and nuclear fuels for the nuclear power industry under prototypical irradiation conditions. Very high-energy neutrons, having a velocity greater than about 6,000 km/s, displace atoms and cause changes in the microscopic structure of materials. These microstructural changes accumulate over long periods of time in radiation environments, with the rate of change depending on the neutron flux. Given the consequences of material failure in many applications in the nuclear power industry, it is necessary to experimentally confirm material performance after long radiation exposures. To avoid impractically long irradiation times, neutron fluxes in the experiment must be much higher than those experienced in the normal operating environment. For a material that is designed to remain in a power reactor for up to 60 years, even a flux level 20 times higher than the power reactor requires 3 years of irradiation to adequately confirm its behavior, hence the need for HPRRs for this application.

MTR studies help establish the safety of power reactors and validate fuel behavior in operational and accident situations. Examples of materials testing include the following:

- Nuclear reactor fuel, including new high-density fuels for HPRRs;
- Metals used in power reactors (such as the steel for pressure vessels) to determine the service lifetime; and
- Electronics expected to operate in high-radiation environments.

Fuel and materials testing supports exploration of advanced materials to further improve safety and performance for the existing fleet of power reactors. In addition, advanced reactor concepts often combine novel fuel,

cladding, and coolant materials, requiring irradiation experiments to confirm their performance under reactor conditions.

MTRs are used to test the behavior of new fuels—including the new low enriched uranium (LEU) fuels that will be used in conversion of research reactors. The fuels are irradiated across a set of conditions that simulate the fuels' expected operating and accident scenario conditions. For this reason, MTR neutron fluxes need to be large enough for significant radiation doses to be delivered in a relatively short time. MTRs have multiple test positions located within and near their cores so that test samples, including full-scale fuel elements and assemblies, can be irradiated under neutron spectra and gamma-to-neutron ratios that are relevant to the fuel or structural material under test. The Advanced Test Reactor (ATR) in the United States, BR2 in Belgium, and MIR.M1 in Russia are particularly important high-flux research reactors used for materials testing.

Materials testing is focused almost exclusively on understanding the impacts of reactor radiation environments on fuels and structural materials. Obviously, reactors themselves provide an ideal environment for such testing, particularly when the tests are sensitive to neutron and gamma spectra, or the ratio between them. Nevertheless, other systems have been proposed for performing materials irradiation in reactor-like environments.

Enhancements to large accelerator-based systems (e.g., the Los Alamos Neutron Science Center and the Spallation Neutron Source [SNS]) can provide modest irradiation volumes with conditions that are adequate for some types of materials testing. These may be appropriate for the smallest-scale irradiation experiments but do not allow for full-plate or element-scale experiments. In addition, it is difficult to use accelerators to produce the same kinds of material damage that are present in reactors because the neutron spectra are significantly different.

In general, research reactors are preferred for materials testing experiments because their neutron spectra are best matched to the expected operating environments. Different neutron energy spectra may produce different numbers of atomic displacements and different amounts of transmuted material. The materials properties will depend, in general, on both.

Extracted Beam Applications

Beams of neutrons are extracted from the research reactor via an evacuated metal tube that extends through reactor shielding. This allows neutrons produced in the core to be used outside of the reactor for a number of scientific applications.

Neutron imaging applications use beams of neutrons to produce images of neutron attenuation, just as a dental radiograph produces an image using x-ray attenuation. Neutrons and x-rays interact differ-

ently with materials: x-ray transmission through a sample decreases with increasing atomic number but neutron absorption does not. This makes thermal and cold neutrons[3] ideal for imaging materials containing light atoms such as hydrogen, which make up a significant fraction of both biological and organic materials, but which are essentially invisible to x-rays. One example is the study of the location of water within a working fuel cell (Satija et al., 2004).

Neutron scattering has been used to probe the structures of materials and the motions of atoms in materials since the first nuclear reactors were built. Neutrons are neutral particles that interact with nuclei in a material sample, so they penetrate materials easily, providing information about the interior rather than the surfaces of materials. The weak interaction allows neutrons to pass through containers needed to keep samples at a particular temperature or pressure. A recent example is the study of the movement of lithium ions in a working lithium-ion battery (Wang et al., 2012). Neutrons interact with atomic nuclei and are scattered differently by different isotopes of the same element. In addition, neutrons are sensitive to magnetism within a sample and can be used to produce maps of internal magnetization.

Over the past six decades, neutron scattering experiments and techniques have improved basic scientific understanding in condensed matter physics, chemistry, polymer science, life sciences, sustainable energy research, sensors, smart materials, mechanical engineering, archeology, nanotechnology, and biotechnology. Examples range from the determination of the atomic structure of the first high-temperature superconductor through verification of theories that describe the distribution and motion of molecules in a melted polymer. Several Nobel Prizes have been awarded for scientific work that rests ultimately on experimental data obtained with neutron scattering.

Neutron scattering is a signal-limited technique, meaning that the quality and quantity of information that can be obtained is limited by the number of neutrons of a particular energy that can be directed at the sample under study. Many advances in neutron instrumentation have been made over the years to improve both the number of neutrons available to the experiment and their utilization.[4] For example, while early investigators were able to break new ground by demonstrating the simplicity of the arrangement of magnetic atoms in antiferromagnetic crystals whose sizes were measured in inches, more recent groundbreaking work has focused

[3] Cold neutrons have speeds of less than 1 km/s.

[4] However, the in-core and near-core applications cannot benefit from improvements in beamline instrumentation for increased flux; for those applications, neutron flux depends on the reactor design and sample placement.

on phenomena occurring in much smaller samples, such as magnetism in layers only a few nanometers thick (Grutter et al., 2015). Since the signal obtained using neutron scattering scales as the amount of material exposed to a neutron beam, experiments on thin layers are much more challenging. Because the neutron-scattering signal is limited by the neutron flux that can be directed at a sample, its most advanced implementation is restricted to high-intensity neutron sources, either HPRRs or advanced pulsed spallation neutron sources.

High-power spallation sources utilize protons from a particle accelerator to bombard a target made of a heavy element such as tungsten or mercury. One advantage of spallation sources is that enriched uranium fuel is not needed to create neutrons. On the other hand, it is currently very difficult to use the spallation process to produce the neutron fluxes that can be generated by the fission of uranium-235 (^{235}U). For many neutron-scattering investigations of materials, this limitation can be addressed by compressing the neutrons into sharp, intense pulses ("pulsing" the accelerator).

There has been a long debate within the neutron-scattering community about the relative merits of research reactors and pulsed spallation sources. The emerging consensus is that, although a rough comparison can be given, the true relative merit depends on the application being considered. For many neutron-scattering experiments, a 1-MW pulsed source such as the SNS has a performance comparable with that of a high-flux research reactor.

Present-day spallation sources do not provide the same time-averaged neutron flux as do high-flux research reactors (also called HPRRs). The neutron-scattering research community has supported the need for both types of neutron sources to provide the full range of capabilities required for modern materials research using neutron scattering. However, this may change over the coming decade because the European Spallation Source[5] (ESS), currently under construction in Sweden, is designed to produce the same average neutron flux as current HPRRs. For now, however, there is no alternative to research reactors for some extracted beam applications.

Finding 3: Research reactors fulfill important missions ranging from education to basic scientific research and medical isotope supply. Other mechanisms for producing neutrons to fulfill all of these missions at similar energies and spectra and average fluxes do not currently exist.

[5] See https://europeanspallationsource.se/.

OVERVIEW OF HIGH PERFORMANCE RESEARCH REACTORS

Over many decades, several research reactors were designed and constructed to achieve very high neutron fluxes to address the purposes outlined above. These reactors tend to have very compact cores to maximize peak power densities and peak neutron fluxes. In addition to the summary in Table 3.1, a brief description of each reactor and its mission is given below.

TABLE 3.1 High Performance Research Reactors of Relevance to the Conversion Study

Research Reactor (Neutron Source)	Location	Start of Operations	Thermal Power (MW)	Maximum Neutron Thermal Flux ($n_{thermal}/cm^2$-s)
MITR-II	MIT, Cambridge, MA	1958	6	6.0×10^{13}
SM-3	RIAR, Dimitrovgrad, Russia	1961	100	5×10^{15}
BR2	SCK·CEN, Mol, Belgium	1963	70	up to 10^{15}
HFIR	ORNL, Oak Ridge, TN	1965	85	2.2×10^{15}
MURR	University of Missouri, Columbia	1966	10	6.0×10^{14}
ATR	INL, Idaho Falls, ID	1967	100–250	8.5×10^{14}
MIR.M1	RIAR, Dimitrovgrad, Russia	1967	100	5.0×10^{14}
RHF	ILL, Grenoble, France	1967	58	1.5×10^{15}
NBSR	NIST, Gaithersburg, MD	1969	20	4.0×10^{14}
FRM-II	Technische Universität München (TUM), Munich, Germany	2004	20	8.0×10^{14}
JHR	CEA/Cadarache, France	2020	100	5.0×10^{14}

SOURCES: For values of thermal power, the following sources are identified for each reactor:
MITR-II: http://web.mit.edu/nrl/www/reactor/reactor.htm
SM-3: NRC (2012)
BR2: Joppen et al., (2011). NOTE: 100 MW is the maximum thermal power, but BR2 is normally operated up to 70 MW.
HFIR: Primm et al. (2009)
MURR: Foyto et al. (2012)
ATR: IAEA Research Reactor Database (RRDB), https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx
MIR.M1: IAEA Research Reactor Database (RRDB), https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx
RHF: http://www.igorr.com/scripts/home/publigen/content/templates/Show.asp?P=764&L=EN
NBSR: IAEA RRDB
FRM-II: Böning et al. (2004)
JHR: http://www.cad.cea.fr/rjh/general-description.html.

MIT Research Reactor

The MIT Research Reactor (MITR-II) has operated since 1958. In 1974, the MITR-I was shut down to allow conversion to MITR-II, which offered a higher neutron flux. Major upgrades included new fuel element design, reactor core tank, and core housing. In 2010, a new operating license was issued for a power upgrade from 5 to 6 MW. The primary uses of MITR-II are advanced materials, fuel, and instrumentation irradiation tests using in-core experimental facilities, although beam ports are also available for other neutron science applications. Its primary sponsor is the DOE Office of Nuclear Energy through the Nuclear Science User Facilities (NSUF) research grants, small business innovation research, and national laboratories. MITR-II is regulated by the U.S. Nuclear Regulatory Commission (USNRC).

SM-3

The reactor facility is located at the site of the Joint Stock Company "State Scientific Center—Research Institute of Atomic Reactors" (JSC "SSC RIAR," hereafter abbreviated as "RIAR"), Dimitrovgrad, Russia. It has been in operation since 1961. It is a pressure-vessel-type reactor. The reactor facility is mainly designed for the production of heavy transuranic elements but is also used to accumulate isotopes with high specific activity and to test materials. The SM-3 uses HEU uranium oxide (UO_2, 90 percent enriched) fuel dispersed in a beryllium-copper matrix.

Belgian Reactor 2

The Belgian Reactor 2 (BR2) has been operated by the Belgian Nuclear Research Center, or SCK·CEN (equivalent to a U.S. DOE national laboratory in Belgium), since 1963. BR2's power limit is 100 MW, but it is generally run between 60 and 70 MW. BR2's primary mission is in-core irradiation experiments, with a particular focus on radiation damage of materials. It is used for radioisotope production and neutron transmutation doping silicon production; these activities generate commercial revenue to supplement the sponsored amounts from the Belgian Ministry of Energy (at a ratio of 60/40). It is a leading location for accelerated testing of materials for nuclear energy applications, including fuel for LEU conversion of research reactors. The primary sponsor for BR2 is the Belgian Ministry of Energy.

High Flux Isotope Reactor

The High Flux Isotope Reactor (HFIR) has been operated by the Oak Ridge National Laboratory since 1965. HFIR was originally constructed for the production of heavy transuranic isotopes requiring multiple neutron captures, for example, ^{252}Cf. Although it is still the only reactor outside of Russia to efficiently produce such isotopes, its mission is currently dominated by neutron-scattering experiments following the installation of a cold neutron source in one of its beamlines. HFIR is sponsored and regulated by DOE.

The University of Missouri Research Reactor

The University of Missouri Research Reactor (MURR) has operated since 1966. MURR is specifically designed for in-core irradiation. Although the reactor still performs this mission, its focus has shifted to medical isotope production. In addition to revenue from commercial customers, MURR is sponsored by the DOE Office of Nuclear Energy and regulated by the USNRC.

Advanced Test Reactor

The Advanced Test Reactor (ATR) has been operated by Idaho National Laboratory since 1967. ATR is the only U.S. research reactor capable of providing large-volume, high-flux neutron irradiation in a prototype environment. ATR allows for the study of effects of intense neutron and gamma radiation on reactor materials and fuels. ATR has many uses, supporting a variety of government- and privately sponsored research. ATR was specifically designed for in-core irradiation to test the performance of materials under naval reactor conditions. In 2007 ATR became an NSUF, and approximately 50 percent of its irradiation positions have been made available in support of this wider user group. ATR is the primary U.S. location for irradiation testing of LEU conversion fuels. ATR maintains a critical facility (ATR-C) with an identical configuration.[6] ATR is sponsored jointly by the DOE National Nuclear Security Administration (NNSA) Office of Naval Reactors and the DOE Office of Nuclear Energy. Both ATR and ATR-C are regulated by DOE.

[6] ATR-C's role requires it to be identical to ATR. Although ATR-C is not technically an HPRR, it is often included in the U.S. accounting of its HPRRs. This report follows this convention.

MIR.M1

The reactor facility is located in RIAR, Dimitrovgrad, Russia. It has been in operation since 1967. It is a channel-type reactor immersed into a pool of water. The reactor facility is equipped with experimental loops having coolants of various types and is designed mainly to test materials under irradiation conditions. MIR.M1 uses HEU UO_2 (90 percent enriched) fuel. Feasibility studies for its conversion are in progress.

High Flux Reactor

The High Flux Reactor (Réactor à Haut Flux [RHF]) has been operated by the Institut Laue-Langevin (ILL) since 1971. The primary mission of RHF is to produce neutron beams to conduct neutron science supported by more than 40 instruments in a reactor hall plus two guide halls. It provides data for approximately 600 refereed scientific publications per year, making it one of the most scientifically productive neutron facilities of any kind. ILL and RHF are sponsored jointly by the governments of France, Germany, and the United Kingdom.

Neutron Beam Split-Core Reactor

The Neutron Beam Split-Core Reactor (NBSR) has been operated by the National Institute for Standards and Technology Center for Neutron Research since 1969. The primary mission of NBSR is to produce neutron beams for the purpose of scientific research, currently supported by 28 instruments on beamlines in two guide halls, producing more than 300 scientific publications per year. NBSR is sponsored by the Department of Commerce and regulated by the USNRC.

Forschungs-Neutronenquelle Heinz Maier-Leibnitz-II Reactor

The Forschungs-Neutronenquelle Heinz Maier-Leibnitz-II reactor (FRM-II) has been operated by the Technische Universität München since 2004. FRM-II is host to five irradiation facilities, a medical application facility, and more than 30 instruments, in operation or under construc-

tion, dedicated to neutron beam science. Basic scientific investigations take up about 70 percent of the available capacity, with the rest dedicated to applied science.

Jules Horowitz Reactor

The Jules Horowitz Reactor (JHR) is under construction at CEA Cadarache and is scheduled to begin operations in 2020. JHR was initially designed to operate using a very high-density LEU dispersion fuel, which is currently under development but not yet qualified and will not be commercially available for the start of JHR operation. JHR will begin by performing tests for 2 years using currently qualified LEU fuel. Afterwards, JHR will operate at nominal conditions, at a power between 70 and 100 MW, using an alternate fuel that provides neutronic equivalence (such as HEU fuel). The mission of JHR will be material and fuel testing as well as radionuclide production for medical applications.

PLANNING FOR NEXT-GENERATION RESEARCH REACTORS AROUND THE WORLD

Europe has seen regular renewal of its HPRR capability, with research reactors commissioned 48, 35, and 11 years ago, and several new reactors planned to begin operation within 5–15 years. In addition, a large spallation neutron source (ESS) is scheduled to begin operation in 2019, and the spallation source at ISIS[7] has recently been upgraded with an additional target station.[8] RHF at ILL has long been a leading facility for neutron science reactor applications worldwide and has been significantly upgraded at various times during its history.[9] For materials testing, BR2 is an important international resource, including for the testing of the high-density monolithic UMo fuel being developed by the United States during periods when ATR is unavailable. Its operator acknowledges, however, that BR2 will likely reach end of life within the next 15–20 years. In light of this eventuality, SCK·CEN in Belgium is planning a new facility to replace BR2, MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications), which is intended to be a particle accelerator-driven nuclear reactor. MYRRHA will focus on materials testing for fissile and fusion systems and

[7] ISIS is a pulsed neutron and muon facility. "ISIS" is not an acronym. See http://www.isis.stfc.ac.uk/.

[8] The situation is not so hopeful for European medium-power (less than 20 MW) reactors, with many of these (e.g., Riso, Julich, Sudsvik) shut down in recent years and others in a precarious state.

[9] However, ILL will be approximately 65 years old when high-density LEU fuel is expected to become available.

on research into nuclear waste treatment through transmutation. The European Commission considers MYRRHA to be a "high priority international project with significant societal relevance." The goal is for this reactor to be operational in 2025.

JHR will also add to European materials testing and irradiation capability but will not support extracted beam applications. Finally, the 45-MW High Flux Reactor at Petten, the Netherlands (previously converted to LEU fuel, and so it is not discussed above) is recognized to be reaching its end of life, and so a new reactor, PALLAS,[10] is being planned for medical isotope production and nuclear technology research. A bidders' conference was held in August 2015; design, construction, and commissioning are expected to take about 10 years. The continuing planning and construction of new HPRRs and other neutron sources in Europe positions it well to maintain its prominence in neutron science and materials testing for decades to come.

Russia, too, is planning new reactor construction, although its emphasis is on fast reactors. The multipurpose sodium-cooled fast neutron research reactor (MBIR) (which has begun construction at RIAR in Dimitrovgrad, but is not an HEU-fueled reactor) will be a 150-MW, sodium-cooled fast reactor and will have a design life of up to 50 years. It will be a multiloop research reactor capable of testing lead, lead-bismuth, and gas coolants, and running on mixed oxide (MOX) fuel. It is expected to begin operations in 2020.

South Korea is in the midst of construction of the Kijang Research Reactor (KJRR), which will be a 15-MW reactor designed for radioisotope production and semiconductor doping. Scheduled to begin operation in 2017, it will be the first reactor in the world to operate on UMo dispersion-type LEU fuel (see Chapter 4). The fuel is being developed in South Korea in parallel with reactor planning and construction.

Aging of the U.S. Fleet of High Performance Research Reactors

The average age of reactors within the U.S.-based HPRR (USHPRR) fleet is close to 50 years. Many of the USHPRRs have recently completed license renewals that last for 20 years, but they will be due for relicensing at about the same time as their conversions to LEU fuel are expected to occur. Physical limits for existing reactors include embrittlement of the containment vessel and cooling systems. A variety of refurbishment strategies and programs (DOE, 2013b) have ensured that these reactors can continue to operate safely and can meet the evolving needs of their users.

The committee gathered end-of-life analysis information from each USHPRR. The operators of these reactors are confident that they can con-

[10] See http://www.pallasreactor.com/?lang=en.

tinue safe operations beyond the next license renewal. In the absence of any plan to replace their capabilities, their roles in support of science, engineering, and medicine missions will be just as important as they are today. Two of the USHPRRs, HFIR and NBSR, have reported an expected end of life near the 2050 time frame and have begun presenting concepts for the next generation of research reactors (Beierschmitt, 2009; Wu et al., 2014). Several others (including ATR and MURR) have indicated no expected end date as long as maintenance and longevity plans are supported. Still, one might readily consider aging as an obstacle to conversion. It is natural (and expected) for operators and those involved in the conversion programs to consider the costs of conversion of a reactor that will operate for only several years before reaching its end of life versus investment in other areas such as new reactor (or other research facilities) planning and design.

No new HPRRs have been fully designed, built, or commissioned in the United States for more than 46 years. USHPRRs will be between 58 and 69 years old by the time that LEU fuel is projected to be available for their conversion. This is an unprecedented age for research reactors, and significantly longer than the projected operating lifetimes for European research reactors. For neutron science applications, ongoing improvements to existing reactor facilities (e.g., the new guide hall at NBSR) have enabled the missions of these facilities to keep pace with the evolving science needs. Changes and augmentation in the science and engineering missions of some HPRRs have been successful, even if they were originally optimized for another purpose. That said, a purpose-built reactor may offer additional benefits and capability over one that has been "repurposed."

Within the United States, a number of reactor facilities have been closed and a few other facilities have been built to support the neutron beam science mission, most notably the SNS. There is also an ongoing effort to construct new facilities for medical isotope production, especially ^{99}Mo. In contrast, no new capability has been developed for other transmutation applications or materials testing.

Finding 4: The mission and capability of some high performance research reactors have evolved to accommodate changing user needs and to expand the user base, with the consequence that the reactors are sometimes not specifically designed for current missions.

Current analyses indicate that the variety of missions spanned by the USHPRRs can be accomplished with the reactors operating with a new high-density monolithic LEU fuel. Similarly, LEU conversion plans for European HPRRs, as well as plans for construction of new European HPRRs using only LEU (or alternatives not requiring HEU), indicate that the HPRR mission space can be preserved using the high-density UMo

dispersion fuel currently undergoing development. This evidence supports the contention that such missions could be accomplished with new research reactors designed specifically to use such fuel, especially if such designs were optimized for the current and expected future missions. Although a rigorous design study has not been completed, it is reasonable to expect that there would be fewer technical constraints in designing a new reactor using a new LEU fuel than there would be in developing a new LEU fuel for existing HPRRs. As noted previously, JHR, an HPRR, was designed for use with high-density LEU fuel, but it will likely begin full operations using HEU fuel because the high-density LEU fuel is not yet qualified. Although it has not been definitively established, it may also be possible to design a new research reactor to satisfy current missions with currently qualified lower-density LEU fuel.

USHPRRs serve different communities and are operated under the auspices of different government offices. Although this arrangement has ensured that each of the important and existing customer bases for research reactors has at least one HPRR that serves its needs, it also means that communication and coordination among the full research reactor community—operators, users, and sponsors—in the United States is difficult and limited. As an example, a DOE Nuclear Energy–National Nuclear Security Administration Research Reactor Working Group[11] in 2013 considered future options for research reactors in the United States, but explicitly recognized that it could only consider reactors and applications within DOE's scope of responsibility (DOE, 2013b). Also discussed previously, operators from individual reactors have begun to propose next-generation designs of research reactors with similar missions (HFIR, managed by DOE, and NBSR, managed by the Department of Commerce), seemingly without coordination across the different agencies that manage these reactors.

There has been no attempt of which the committee is aware to consider and prioritize needs for research reactors in general or HPRRs in particular across all U.S. stakeholder communities. The Office of Science and Technology Policy (OSTP) was established in 1976 via legislation[12] that authorizes the office to lead interagency efforts to develop and implement sound science and technology policies. OSTP therefore both supports the advancement of basic and applied science and has the ability to gather cross-agency insights, much more so than the individual agencies by themselves. Until such broad engagement and community priority setting takes place, it is

[11] While the usual acronym for the National Nuclear Security Administration is "NNSA," the group formed by the DOE Nuclear Energy and National Nuclear Security Administration is referred to as the "NE-NA Working Group" instead of the "NE-NNSA Working Group."

[12] See the National Science and Technology Policy, Organization, and Priorities Act of 1976 (P.L. 94-282).

likely that the USHPRRs will operate in "run-to-failure" mode without a smooth transition to the next generation of research reactors or research facilities capable of similar missions. The result would likely be that the United States will lose capability and international presence in important areas of scientific and technological research. It is worth mentioning that other technical communities have demonstrated the possibility of reaching a community consensus on priorities for major facilities, as illustrated by the recent Particle Physics Project Prioritization Panel (P5) report of the particle physics and particle astrophysics communities.[13]

Finding 5: There is no overarching, cross-agency, long-term strategy for meeting enduring U.S. need for research reactors. The nearly 20-year time line to conversion that is currently estimated for some of the U.S. fleet of high performance research reactors is much longer than was originally estimated and coincides with many of the reactors' time lines for relicensing. At that time, these reactors will be on average 65 years old. Because of the convergence of relicensing, conversion, and aging issues of the current U.S. high performance research reactors (USHPRRs) in 2030, it is reasonable to compare the benefit of converting/retrofitting the current fleet of USHPRRs against designing and building new research reactors that use low enriched uranium fuel and address the critical missions the current reactors support.

Recommendation 1: The U.S. Office of Science and Technology Policy should take the lead in developing a 50-year interagency strategy that enumerates and evaluates the importance of anticipated U.S. civilian needs for neutrons and provides a roadmap for how these can best be provided by reactors and other sources that do not use highly enriched uranium.

[13] Available at http://www.usparticlephysics.org/p5/.

4

Technical Obstacles to Conversion

The conversion of a research reactor's fuel from highly enriched uranium (HEU) to low enriched uranium (LEU) follows a set of general steps that can each present technical and/or nontechnical obstacles to conversion. This chapter outlines the general steps to conversion, the principles that define the conversion for each reactor, the constraints that result from those principles, and a discussion of reactors for which the main challenge to conversion is technical. The committee presents several ideas for overcoming the technical obstacles to conversion. The nontechnical obstacles to conversion are addressed in Chapter 5.

BASIC STEPS TO CONVERSION

Altering the fuel of an existing operating research reactor (to LEU or other types) requires many steps and consideration of both technical and nontechnical factors (e.g., reactor performance, economics, licensing). The general steps of reactor fuel conversion, shown in Figure 4.1, are as follows:

1. Negotiation by decision makers and reactor operators to initiate the conversion process followed by a political decision to consider reactor conversion.
2. A feasibility study to assess whether conversion is possible.
3. An official decision to convert.
4. Completion of detailed operational and safety analyses for licensing.
5. Regulatory review for conversion.
6. Response to the regulator's questions.

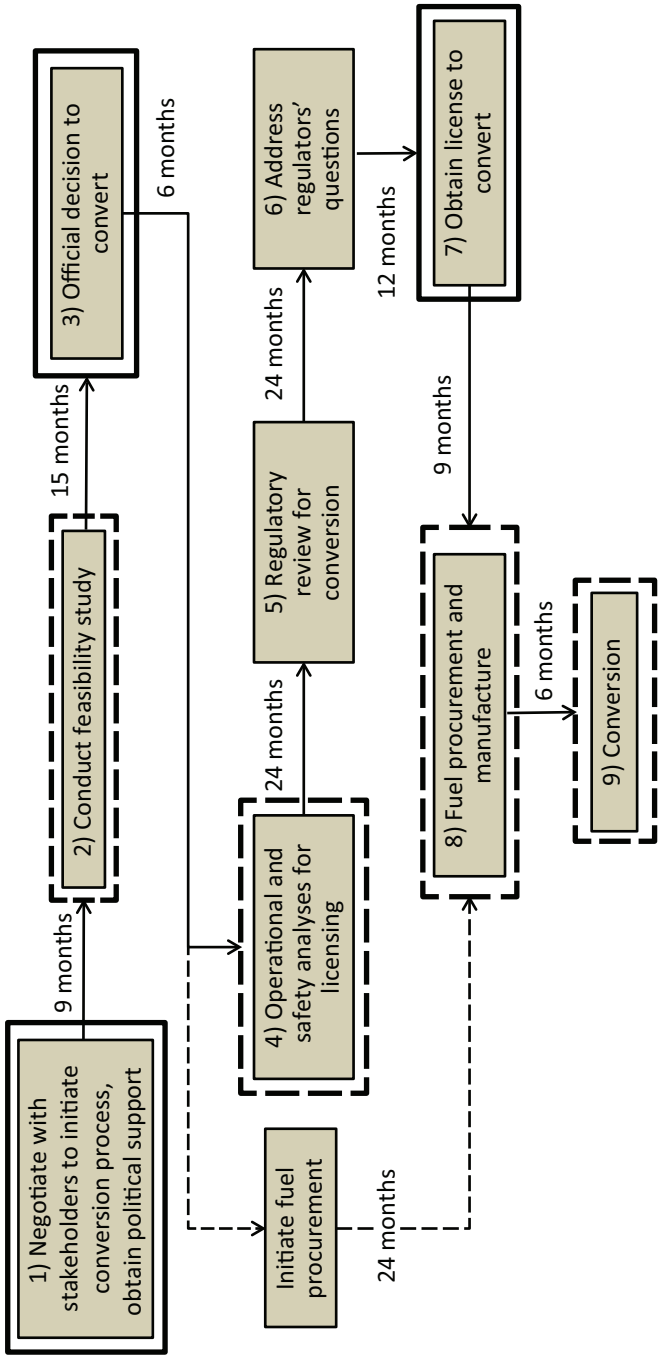

FIGURE 4.1 General steps to reactor conversion to LEU fuel. Steps dominated by nontechnical issues are surrounded by a solid line (Steps 1, 3, and 7). Technical steps are surrounded by a dotted line (Steps 2, 4, 8, and 9). Not shown: fuel development and qualification steps and time estimates. SOURCE: Office of Material Management and Minimization Office of Conversion, used with permission from the National Nuclear Security Administration (DOE).

7. Granting of a license to convert.
8. Fuel procurement and manufacture.
9. Conversion.[1]

Fuel procurement proceeds along a parallel path (see Figure 4.1). Estimates of the time for each step are included in the figure. Using these estimates one could assume that, in general, conversion takes less than 9 years. Notably, the figure and this list do not include the steps and time required to develop and qualify a new LEU fuel. Fuel development and qualification, as will be shown in this chapter, are significant technical hurdles in the conversion process.

PRINCIPLES OF FUEL ACCEPTABILITY FOR CONVERSION

An assessment of the feasibility of reactor conversion involves technical steps that are guided by a set of principles intended to encourage cooperation of reactor operators and regulators and to assure the safe and acceptable operation and performance of the converted reactors. "Principles of fuel acceptability" have been used by the U.S. conversion program to assure that "a fuel assembly must be *qualified*, *commercially available*, and *suitable* for use in that reactor" (Stevens, 2014, p. 5).

After these principles have been met, the next step is for the reactor operator and regulator to agree to accept the fuel assembly for conversion. The italicized terms are defined as follows (Stevens, 2014, p. 5):

- *Qualified fuel assembly*—a fuel assembly[2] that has been successfully irradiation tested and is licensable[3] from the point of view of fuel irradiation behavior.
- *Commercially available fuel assembly*—an LEU fuel assembly that is available for purchase from a commercial manufacturer.
- *Suitable fuel assembly*—a fuel assembly that satisfies criteria for LEU conversion of a specific reactor, including the following:
  - Fuel service lifetime comparable to current HEU fuel (e.g., number of fuel assemblies used per year is equal to or fewer than with HEU fuel);

[1] The Global Threat Reduction Initiative (GTRI)/Office of Material Management and Minimization (M^3) conversion programs define a reactor as "converted" once the first LEU fuel assembly is inserted into the reactor core.

[2] For U.S. reactors, the term *fuel element* refers to a collection of fuel plates that are grouped together to form a single unit. For Russian reactors, the term *fuel element* refers to the fuel plates, tubes, or rods. To avoid confusion, the text uses the term *fuel assembly* to describe a collection of *fuel plates*.

[3] Licensing requirements may vary depending on the regulator and the country.

— Satisfaction of safety criteria; and
— Technical and economic performance not significantly impacted by LEU conversion so that the reactor can continue to meet its mission.

Conversion may also require addressing licensing issues or additional nontechnical issues associated with conversion (Roglans, 2014).

The original International Nuclear Fuel Cycle Evaluation (INFCE) language echoes this approach (INFCE, 1980, p. 18):

> In assessing the practical feasibility of utilizing lower enriched fuel in existing research reactors, the agreed criteria are that safety margins and fuel reliability should not be lower than for the current design based on highly enriched uranium and that neither any loss in reactor performance, e.g., flux-per-unit power, nor any increase in operating costs should be more than marginal.

Reactor Performance Constraints and Associated Technical Challenges for Conversion

The three categories of performance constraints derived from the suitability of a fuel assembly for a given reactor drive many of the technical challenges for conversion.

Fuel Service Lifetime and Reactivity

The sustained fission of uranium-235 (^{235}U) in a reactor core allows a reactor to operate. Like the fuel in an automobile's fuel tank, which does not limit the car's speed, but determines whether it can be started and how far it can go, there is a minimum amount of ^{235}U needed to start the reactor (i.e., go critical) and keep it running. The reactor cycle length is the amount of time from initial criticality until a chain reaction can no longer be maintained and the reactor must be shut down for refueling. If there is insufficient ^{235}U, then the reactor either cannot start or its cycle length will be too short, like a car with a 1-gallon fuel tank.

Typically, cycle length is an economic issue for two reasons. First, cycle length affects mission performance because frequent refueling will decrease the amount of time that the reactor will be available to produce neutrons. Second, longer cycles translate to lower fuel consumption (and therefore lower annual fuel procurement costs).

The minimum amount of LEU that must be present in a given fuel assembly to replace an existing HEU fuel assembly can be roughly estimated. The ratio of mass per element, M_{LEU}/M_{HEU}, has to be at least as

great as the enrichment ratio, e_{HEU}/e_{LEU} = 4.7 (assuming an enrichment of 93 percent and 19.75 percent for HEU and LEU, respectively) in order to preserve the amount of ^{235}U. In fact, this ratio has to be multiplied by a factor $f_{penalty}$ (which is greater than 1) to account for different penalties, such as the following:

- Uranium-238 (^{238}U) (the dominant uranium isotope) is a neutron absorber for thermal neutrons. Additional ^{235}U is needed in the new fuel because LEU fuel has significantly more ^{238}U than does HEU fuel for the same volume.
- The minor elements in the fuel compound can bring some additional penalties because of their nuclear cross section. For example, in the thermal domain, Mo captures 10 times more neutrons than Al.
- The power of the reactor often must be increased to retain local performance specifications after conversion, and consequently, the mass of ^{235}U has to be increased to keep the same cycle length (more gas in the tank for a higher operating power).[4]

This factor, $f_{penalty}$, can vary from 1.2 to 2.0, depending on the specific reactor.

Thus, to replace 1.0 kg of HEU in a fuel assembly, 5.6 to 9.4 kg of LEU is needed in the example above, but the actual values will depend on the details of the LEU and the core configuration of each reactor.[5]

Safety Constraints

Given an amount of ^{235}U that will satisfy the reactivity and service lifetime constraints, safety margins for LEU fuel must also be satisfied. Some safety analyses are based primarily on neutronics calculations to confirm that the reactivity coefficients, the control element worth, and the reactivity insertions associated with experimental facilities are within the required margins. Safety analyses include thermal hydraulic calculations to show that the coolant flowing through and between the channels within the fuel assembly can remove the heat being generated by the fuel plates. HEU fuel assembly designs for high performance research reactors (HPRRs) rely on high coolant velocities through narrow channels to remove the heat generated by the high-power core. Current thermal hydraulic analysis techniques

[4] The option to increase operating power to compensate for reduced performance post-conversion was not considered for early conversions in the U.S. and Russian conversion programs, but has since been used. For example, the University of Missouri Research Reactor (MURR) and the High Flux Isotope Reactor (HFIR) plan to increase operating power post-conversion to compensate for reduced LEU performance.

[5] This simple calculation neglects plutonium fission contributions and assumes the fuel geometries between HEU and LEU fuel remain the same.

are validated by long operational experience with the specific fuel assembly geometries of each reactor.

To simplify the thermal hydraulic and, consequently, the safety margin analysis between HEU and LEU fuels, the LEU fuel design usually retains both the contact area of the fuel element–coolant interface and the widths of the coolant channels. Thus, safety constraints for conversion are met by retaining the basic geometry of the fuel assemblies and cooling channels, thereby preserving the validity of existing safety analyses.[6]

Technical and Economic Performance

Since the start of the Reduced Enrichment for Research and Test Reactors (RERTR) Program, maintaining reactor performance after conversion has been a high priority. This is necessary to obtain the support of reactor operators and users. The HPRR cores produce high power densities to achieve the large neutron fluxes (approximately 10^{15} n/cm^2-s) that enable the applications discussed in Chapter 3. In the case of in-core irradiation applications, the flux levels of thermal and fast neutrons may be important, and in some applications the distribution of neutron energies (i.e., the spectrum) at a particular irradiation position is also essential.

The size and geometry of the core must also be preserved because of the location of current in- and near-core experiments, reflectors, and beamlines within or near the existing reactor cores. Assuring that the performance requirements are met necessitates detailed neutronic analyses of proposed LEU core designs that meet the geometric and thermal and fast flux constraints.

Finally, the operational costs of using LEU fuel should not be substantially greater than those for HEU fuel. Operational considerations include cost of fuel and duty cycle of fuel assemblies.

In summary, the list of mission/performance constraints imposed on the conversion are as follows:

- Design the same amount, or more, of ^{235}U into the LEU fuel assembly to maintain cycle length.
- Retain the basic geometry of the fuel assemblies and cooling channels to maintain safety margins.
- Retain the core geometry and size so that existing experiments and beamlines are not affected.
- The expected costs of operations after conversion should marginally compare to costs before conversion.

[6] Although this is true for many HPRRs, MITR-II operators have changed the standard design of its fuel element—by removing the fins. This is one example in which LEU fuel geometry differs from that of HEU.

Implications for Fuel Design

The above constraints have consequences for the LEU fuel that must be developed. The need to increase the total uranium content in the fuel meat (see Box 4.1 and Figure 4.2) by a factor of 5 to 10 while retaining fuel assembly size and geometry is one of the most critical requirements. This could be accomplished by several approaches: increasing the uranium content of the fuel particles within the fuel meat by increasing the density of the U-containing compound; increasing the volume fraction of the particles in the meat (but 50 to 55 percent is a technological limit for the manufacture of dispersion fuel by rolling[7]); changing the fuel type (e.g., by developing a fuel that is "monolithic" and does not need to be dispersed in a matrix); and/or increasing the thickness of the fuel meat (see Figures B4.1 and 4.2).

Many medium-power research reactors have successfully converted using high-density LEU fuel such as silicides (U_3Si_2 and U_3Si). However, the performance requirements of the remaining unconverted HPRRs require still higher uranium densities than were needed for these previous conversions.

For the new LEU fuel to be qualified for use, its behavior over the operating conditions of the reactor must be understood. Both the mechanical and geometric integrity of the fuel must be maintained throughout its expected operational life. The cladding must continue to provide a barrier for fission product transport, and the coolant flow paths must not be affected by changes in the geometry of the fuel assembly. The two characteristics of the reactor environment that most impact these requirements are the local power density and the local fission density (or burnup). The local power density, a parameter related to the irradiation performance requirements, provides the instantaneous driving force for possible failure mechanisms of the fuel system due to instantaneous damage rates and thermal gradients. The local fission density,[8] which is proportional to burnup, provides a measure of the accumulated fission products and fission gases and radiation damage that can lead to failure of the fuel. For each reactor, it is possible to determine the performance envelope (e.g., the highest local power density and the highest local fission density) through detailed neutronics models

[7] The *limit value* or *technological limit* of 50 to 55 percent has been determined and is used by manufacturers of material test reactor (MTR) plate-type fuel (Compagnie pour l'Etude et al Réalilsation de Combustibles Atomiques [CERCA], Babcock and Wilcox Technologies [BWXT]). Values higher than those commonly used by the manufacturers have been found to increase the complexity of the manufacturing process and reduce its yield. Additionally, values significantly greater than 55 percent could increase the risk of in-pile failures because the matrix no longer governs the mechanical and thermal properties of the fuel plate.

[8] The reactor's local fission density (fissions per cubic centimeter [fissions/cm^3]) and burnup (a way to measure the amount of fuel consumed in the reactor, usually expressed in percentage of ^{235}U consumed) are parameters that measure the extent to which the ^{235}U is being consumed throughout the core.

BOX 4.1
Description and Definitions of Terms Related to Fuel Composition

The figure below provides schematics of the two types of research reactor fuel discussed throughout this chapter: dispersion and monolithic fuel. Both schematics are cross sections of plate-type fuel. The dispersion fuel consists of fuel meat encased by a cladding to form the plate (Figure B4.1(a)). The fuel meat consists of particles of a uranium-containing compound or alloy (fuel particles), which are dispersed throughout a matrix. A photo of a dispersion fuel plate in cross section is provided in Figure 4.2. The uranium density of dispersion fuel can be increased by increasing the volume fraction of uranium-containing particles within the fuel meat. Because of processing issues, the maximum volume fraction of these particles is 50 to 55 percent. Uranium density can also be increased by selecting particles with higher uranium density (such as the silicide, U_3Si_2, fuel discussed in the text).

Monolithic fuel is composed of a uranium-containing alloy foil (fuel foil) surrounded by a cladding (Figure B4.1(b)). The text refers to a U-10Mo alloy, which is uranium mixed with 10 percent by weight molybdenum. The density of a fuel foil of a particular alloy is fixed by the alloy composition. Therefore, to increase the mass of uranium in a monolithic fuel plate, the thickness of the fuel foil must be increased.

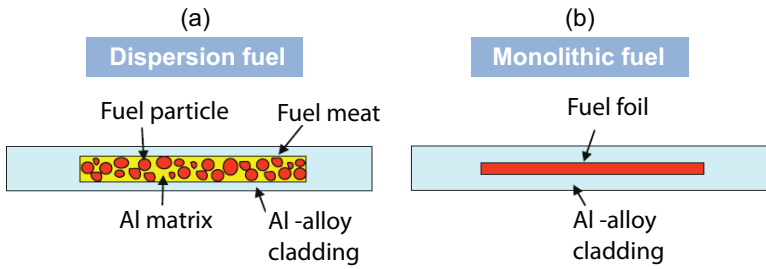

FIGURE B4.1 Schematic cross sections of (a) plate-type dispersion fuel and (b) plate-type monolithic fuel. SOURCE: Office of Material Management and Minimization Office of Conversion, used with permission from the National Nuclear Security Administration (DOE).

and calculations. Figures 4.3 and 4.4 define the performance envelopes for the U.S. and European HPRRs. Although the location of the highest power density may not coincide with the location of the highest fission density and burnup, they can be considered to be conservative bounds on the fuel performance envelope for each reactor.[9] The first step in qualifying a new fuel form is to demonstrate experimentally that the fuel system will main-

[9] Generally, the locations of highest power shift within the core as the control rods are drawn out and burnup is achieved.

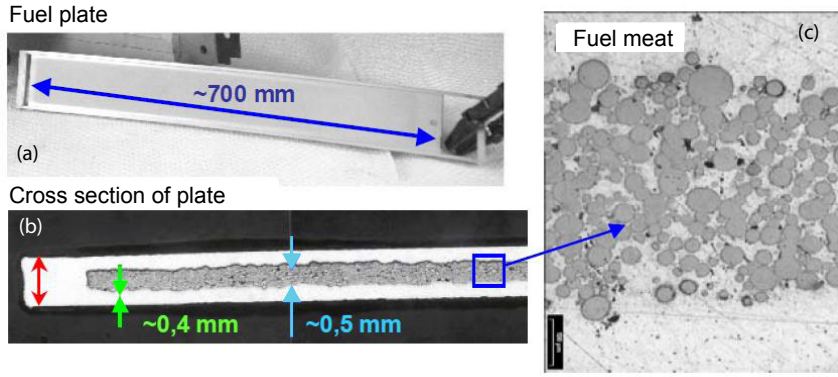

FIGURE 4.2 The photos and micrographs show (a) a fuel plate, (b) the fuel plate cross section showing the fuel meat and cladding, and (c) a closeup of the fuel meat with embedded uranium compound or particles. SOURCE: Modified from Van den Berghe at al. (2015).

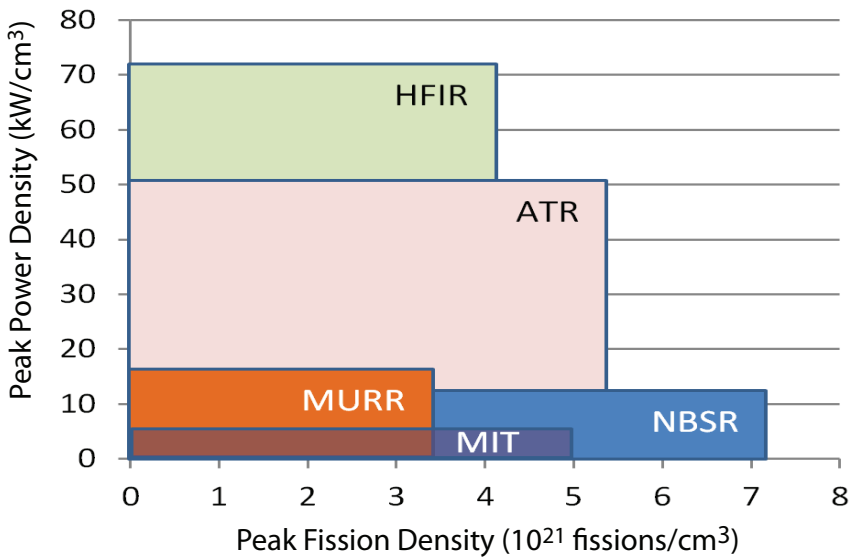

FIGURE 4.3 Fuel operating performance envelopes for the U.S. High Performance Research Reactors. In the figure, the MIT reactor is referred to as simply "MIT," whereas throughout the report it is referred to as "MITR-II." SOURCE: Courtesy of Argonne National Laboratory (Yacout, 2015).

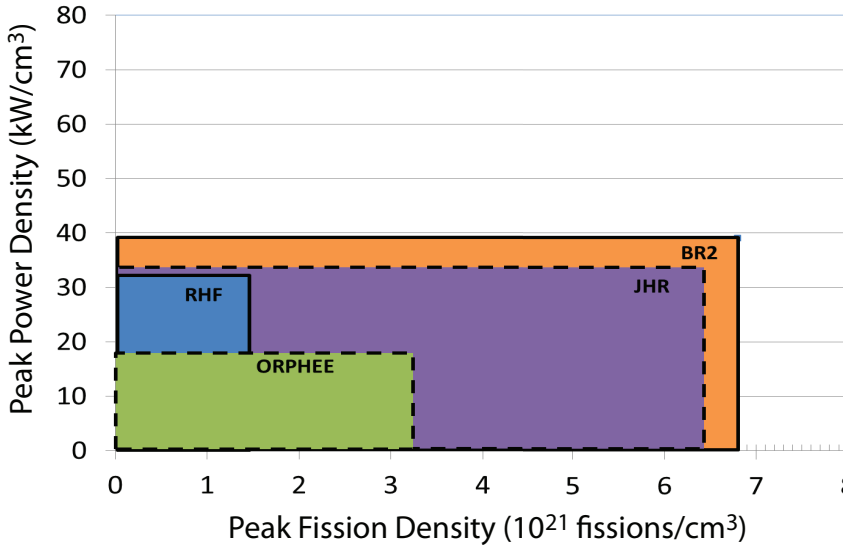

FIGURE 4.4 Fuel operating performance envelopes for four European HPRRs. BR2, JHR, and RHF are expected to convert to high-density LEU fuel after it is qualified. The Orphée reactor is now expected to shut down prior to conversion. SOURCE: Courtesy of Argonne National Laboratory (Yacout, 2015).

tain its integrity under irradiation conditions throughout these envelopes (which include safety margins).

Finally, the cost of the new fuel must be considered. The cost to manufacture the new high-density UMo fuels is not well known. In addition, there is a limited supply of HEU for downblending for civilian applications (20 metric tons), and the United States does not currently have another capability to produce 19.75 percent uranium. Considering the time lines for fuel development, qualification, and conversion, there is some concern that the 20-metric-ton supply will eventually run out.[10]

[10] Parrish Staples, written communication, September 11, 2015: "Currently other U.S. domestic reactors as well as U.S. Government enriched uranium supply agreements and commitments of 19.75 percent supply for foreign research reactors or medical isotope production predominately pull material from the 1994 surplus HEU declaration, and those supplies are expected to be practically exhausted by around 2025. As reactors convert to LEU fuel, it is expected that the usage rate of surplus enriched uranium used to make LEU will increase and additional supplies will be needed. Should the Department [of Energy] decide to use a portion of the [2005 surplus HEU declaration] that had been reserved for [civilian] HEU supply, to make LEU for converted reactors, total supplies could be extended to around 2033."

TECHNICAL CHALLENGES TO CONVERSION: VERY HIGH-DENSITY FUEL DEVELOPMENT

There are seven U.S.-based HPRRs (USHPRRs) that cannot be converted with existing qualified, commercially available LEU fuels (Stevens, 2014).[11] This is also true for the HPRRs in Europe and Russia including the following:

- five European high-flux reactors (BR2, RHF, Orphée, FRM-II, and JHR);
- four Russian-supplied reactors of the IRT-type (IRT-Mephi, IRT-T, IR-8, and IRT-DPRK);
- two reactors that could use the same high-density fuel as the IRTs, but in circular geometry (MIR.M1 and MIR.M1 CA);
- two reactors that were identified requiring high density (probably UMo), but in pin- rather than tube-type form (IVV-2M and WWR-M); and
- six Russian high-temperature reactors that require a unique high-density fuel development/qualification effort (SM-3, SM-3 CA, RBT-6, RBT-10, PIK, and PIK PM).[12]

Consequently, several countries have launched efforts to develop and qualify higher-density LEU fuel that can meet the performance, safety, and operational constraints of these reactors.

Early Fuel Development Efforts

Three main fuels based on HEU were in use when the RERTR Program began in 1978:

- UAl_x powder dispersed in an aluminum matrix (UAl_x-Al dispersion fuel) with uranium compound densities up to 1.7 gU/cm^3,
- U_3O_8-Al dispersion fuel with uranium compound densities up to 1.3 gU/cm^3, and
- $UZrH_x$ alloy fuel with 0.5 gU/cm^3.

UAl_x-Al (or aluminide) fuel was developed at the Idaho National Engineering Laboratory in the 1960s for use in the 250-MW ATR (Advanced Test Reactor). U_3O_8-Al (or oxide) fuel was developed at the Oak Ridge National Laboratory in the 1960s for use in the 100-MW HFIR (High

[11] The reactors are ATR, ATR-C, HFIR, MITR-II, MURR, NBSR, and TREAT; the current fuel development effort is focused on the first six.

[12] Roglans, written communication, September 2015.

Flux Isotope Reactor). $UZrH_x$ (or TRIGA) fuel was developed by General Atomics and used in TRIGA reactors with power levels up to 14 MW. The uranium densities of these fuels, as originally developed, are too low for converting HPRRs while satisfying performance requirements.

The objectives of the original fuel development effort in the RERTR Program were to increase the uranium densities for these existing fuels to their practical limits using LEU (less than 20 percent enriched in ^{235}U), and develop new LEU fuel with even higher uranium densities.[13]

For existing fuels, LEU uranium densities were qualified up to 2.3 gU/cm^3 for UAl_x-Al fuel, up to 3.2 gU/cm^3 for U_3O_8-Al fuel, and up to 3.7 gU/cm^3 for $UZrH_x$ fuel (Travelli, 1989). Each fuel was tested extensively up to, and in some cases, beyond these densities.

The RERTR Program also developed silicide (U_3Si_2-Al) dispersion fuel, which was qualified with uranium densities up to 4.8 gU/cm^3. The U.S. Nuclear Regulatory Commission (USNRC) issued formal approval for use of this fuel in domestic research and test reactors (see Figure 4.5). Many irradiation tests using this fuel have been successfully completed in research reactors around the world, and the fuel has been extensively used for the conversion of medium-power reactors in different countries, including OSIRIS in France in 1997,[14] Japan Materials Testing Reactor (JMTR) in Japan in 1994, High Flux Reactor (HFR) in the Netherlands in 2006, South African Fundamental Atomic Research Installation (SAFARI) in South Africa in 2009, and more recently, MARIA in Poland in 2012.

Selection of UMo Compounds and International Decisions on Fuel Type

By the end of the 1990s, after the first conversions using LEU silicide (U_3Si_2), attention turned to the remaining HPRRs that were unable to use U_3Si_2 without severe performance losses. It was estimated[15] that most of these reactors could be converted with a fuel density of 6.5 to 8.5 gU/cm^3. Some reactors (such as the FRM-II reactor in Germany[16]) required even higher densities, available only in alternative fuel designs. The United States, the main driving force behind the conversion requirements and an

[13] RERTR's original mission was limited to reducing HEU exports by converting U.S.-supplied research reactors to LEU fuel. See Chapter 2.

[14] OSIRIS was first converted in 1980 by using "Caramel" fuel (UO_2, 9 gU/cm^3, 7 percent ^{235}U-enriched). The dates that appear in this list are the dates of the introduction of the first LEU silicide fuel in the reactor core.

[15] Since these first evaluations, neutronic reevaluations were made, specifically for the USHPRRs, and for most of them the minimum required density is now estimated to be 9 gU/cm^3.

[16] The HEU-fueled FRM-II uses high-density silicide fuel originally developed as part of the RERTR Program to enable reactor conversions to LEU.

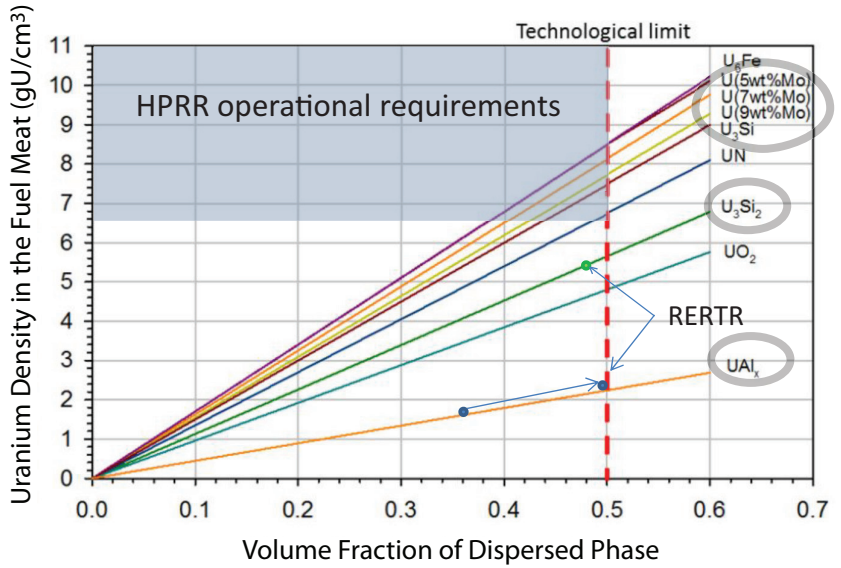

FIGURE 4.5 Uranium density in dispersion reactor fuel as a function of volume fraction (fraction of uranium that is mixed into the dispersed phase). This chart shows RERTR's qualified LEU fuels: the increase in UAl_x density from 1.8 to 2.3 gU/cm^3 is shown by the two blue dots on that curve, and the new silicide (U_3Si_2) fuel at 4.8 gU/cm^3 is shown by a single green dot. For the HPRRs to maintain operational performance, fuel densities of 6.5 gU/cm^3 and higher are required, as shown by the box at the top of the figure. For U_3Si_2, the value 6.5 gU/cm^3 is associated with a volume fraction of particles of 60 percent, which exceeds the technological limit commonly adopted. UMo dispersion fuels are currently being tested for use in the European HPRRs at 5, 7, and 9 weight percent Mo (U-5Mo, U-7Mo, and U-9Mo). The graph includes several common reactor fuels not mentioned in the text, including UN and UO_2. The "technological limit" of 50 percent volume fraction for solid dispersions is shown. SOURCE: Modified from Van den Berghe at al. (2015).

important supplier of HEU,[17] led the efforts with a number of scoping studies to identify appropriate fuel candidates.

Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) and CERCA were first to join U.S. efforts to study high-density dispersion fuels; this collaboration was later extended to other European countries. From 1998 to 2005, it was the "French UMo Group" or "Groupe

[17] The "Schumer Amendment" (Section 903 of the Energy Policy Act of 1992, H.R. 776) limits the U.S. exports of HEU, requiring a commitment to civilian research reactor conversion from the recipient country.

Pentapartite," a French consortium between CEA, CERCA, and three other AREVA subsidiaries. From 2005 to 2008, the agreement was reduced to CEA and CERCA. In 2009, the European consortium was expanded to include Studiecentrum voor Kernenergie·Centre d'Etudes Nucléaire (SCK·CEN) in Belgium, and CEA, CERCA, and Institut Laue-Langevin (ILL) in France; this new consortium was named "LEONIDAS" for "Low Enriched Option Network Initiative for the Development of a European Appropriate Solution." In 2013, the LEONIDAS consortium was further expanded to include a German partner, Technische Universität München (TUM), and formed the HERACLES (Highly enriched European Reactors Action for their Conversion in a Low Enriched Solution) Group.

A number of high-density uranium compounds were subjected to irradiation testing from which the U-xMo alloys were investigated (where x indicates the percent by weight of Mo). The UMo alloys are more malleable at high temperature than silicide fuels and are being investigated as both a dispersion and monolithic fuel (see Box 4.1). The alloys U-7Mo and U-9Mo were chosen as the best candidates for dispersion fuels (see Figure 4.5), while U-10Mo was selected for monolithic fuel.[18] This selection marked the start of a number of validation irradiations to expand the fundamental understanding of the fuels required for qualification.

A UMo dispersion fuel is formed by dispersing small particles of the U-xMo alloy in a base aluminum matrix to form the fuel meat that is then clad with an aluminum alloy. As discussed below, it may be necessary to prevent, or at least reduce, the formation of an unwanted amorphous interlayer between the particles and the Al matrix. This can be done by adding silicon, for example, to the matrix or by coating the particles to ensure the integrity of the fuel.

An important feature of dispersion fuels is the ability to vary the amount of uranium in the fuel (called the "uranium loading" and sometimes referred to as "uranium density") by changing the volume fraction of the UMo powder in the Al matrix. This allows fuel designers to tailor individual fuel plates to their operating environment. Additionally, UMo dispersion fuel is structurally similar to existing fuels, giving it the advantage of a well-understood fuel fabrication process.

A UMo monolithic fuel is formed by sandwiching a foil of UMo alloy, usually with 10 percent by weight Mo, within an aluminum alloy cladding.

[18] The gamma phase of uranium is the only phase stable under irradiation. In the UMo alloy, molybdenum is added to uranium to stabilize this gamma phase. The choice of Mo percentage is a compromise between high values (to stabilize the gamma phase) and low values (to minimize the neutronic penalty of the alloy because Mo has a higher cross section than Al). In addition, as the percentage of Mo increases, the foil malleability decreases for the monolithic form. For dispersion fuel, 7 or 9 weight percentage of Mo is usually chosen, and for the monolithic form, 10 percent is preferred because of the higher temperatures of its manufacturing.

It may be necessary to add an interface layer between the fuel meat and the cladding to maintain the integrity of the fuel plate. Because it is not possible to alter the density (or uranium loading) of the uranium in the fuel meat once the UMo alloy composition has been chosen, fuel designers must rely on changing the UMo foil thickness to achieve the same flexibility in uranium content as with dispersion fuels. A rule of thumb developed by fuel manufacturers allows for a maximum of 50 to 55 percent volume fraction for UMo dispersion fuel; thus, the UMo foil thickness in monolithic fuel needs to be only about one-half as thick as the fuel meat in UMo dispersion fuel to achieve the same uranium content. Because the outer dimensions of the fuel plate are fixed by other constraints, these considerations lead to the need for different cladding thicknesses.

Current estimates of the maximum uranium density achievable in the UMo dispersion fuel are between 8 and 8.5 gU/cm^3 (see Figure 4.5); UMo monolithic fuel can reach uranium densities of up to 15.9 gU/cm^3, dependent on the amount of Mo in the alloy. The dispersion fuel density is sufficient to support the LEU conversion of European HPRRs (with the exception of FRM-II), but is not sufficient for the conversion of all USHPRRs. The M^3 Office of Conversion made a decision to pursue a single fuel for all USHPRRs in an effort to reduce the total development costs and distribute the fixed costs of a fuel production line over all the USHPRRs; this decision is known as the "one-for-all" approach (Robinson et al., 2009; Senor and Burkes, 2014). Therefore, the U.S. conversion program is now focused on the development of the monolithic fuel form, while the HERACLES consortium is focused on the qualification of the UMo dispersion fuel. The European and U.S. LEU fuel development and manufacturing programs have similarities and differences, which are highlighted in Table 4.1.

Apart from the United States and Europe, several other countries are involved in UMo fuel development. South Korea has a complete UMo dispersion fuel program—from manufacturing to irradiation qualification—designed to support its new 15-MW Kijang Research Reactor (KJRR).[19] KJRR is under construction, and it is likely to be the first reactor in the world to use UMo dispersion fuel. Its first criticality is planned for 2018 (Park, 2014, 2015).

Russia also has a large UMo dispersion fuel development program, including manufacturing and in-reactor testing of fuel elements (mini- and full-sized rods) and full-sized assemblies. The most recent experiments were performed in the MIR.M1 reactor on full-sized tube-type elements. The final irradiation tests of two experimental tube-type assemblies are

[19] For this reactor, designers chose a plate-type U-7Mo/Al-5Si dispersion fuel assembly with a density of 8 gU/cm^3 for 19 inner plates, and 6.5 gU/cm^3 for two outer plates of the fuel assembly.

TABLE 4.1 Comparison Between European and U.S. Fuel Development and Manufacturing Programs

	Europe	United States
Management	HERACLES consortium across European Union countries (Belgium, France, Germany)	DOE/NNSA, M^3 Office of Conversion
Organization	Strategic committee (heads of each laboratory) and technical committee	NNSA program management makes decisions based on input from four pillars led by teams of NNSA and DOE lab technical expert leads; four pillars are fuel development, fuel fabrication, conversion, and integration.
Funding	Primary: European Union Secondary: DOE/NNSA through M^3 (this funding is not managed by HERACLES; a large fraction is spent at U.S. labs in support of HERACLES)	U.S. Congress to DOE/NNSA
Review groups	The technical committee has two standing review groups: • Fuel manufacturing expert group • Fuel development expert group Each expert group consists of technical experts within and outside of HERACLES, including U.S. fuel experts.	Independent review teams: • Independent Strategic Review (ISR) • Fuel Development Review • Cost Review Members of the review teams are primarily U.S. experts (see Chapter 6 for more details).
Fuel type	Primary: UMo dispersion fuel Secondary: UMo monolithic (for FRM-II) and high-density U_3Si_2 as a backup	UMo monolithic fuel only
Fuel fabricators	CERCA, a subsidiary of AREVA[a]	BWXT, private company funded by DOE to make research reactor fuel (a small percentage of overall BWXT uranium fuel business), sole supplier to U.S. Navy for submarine nuclear reactor fuel

[a] AREVA is a French company. Recently, CERCA has come under pressure to remain profitable while addressing a need to update facilities and develop capabilities to produce the new, high-

continued

currently in progress and expected to end in 2016. The results, including post-irradiation examinations, of these experiments are anticipated in 2018. Once qualified, Russia plans to sell this fuel commercially to its non-domestic customers (see Chapter 5).

Argentina and Canada also have high-density LEU fuel development efforts. Argentina has been involved in the RERTR Program to develop dispersion or monolithic fuel since 1997. The Argentine National Commission of Atomic Energy (the Argentinian acronym is "CNEA") studied the interaction between UMo and Al-Si alloy by using atomistic simulations and by experimental methods. CNEA focused its research and development program for UMo monolithic fuel on the fabrication technologies of UMo with Zircaloy-4 cladding. Canada was also involved early in the RERTR Program to develop UMo dispersion fuel in Al matrix. Now, Canadian Nuclear Laboratories (CNL) is developing an alternative concept in which the Al matrix is replaced by a magnesium matrix (Wang et al., 2015).

Fuel Testing Overview

Each test of a new fuel can take several years. Time lines for testing depend on details of each test, including the design of the experiment, maturity of the fuel system under test, and availability of space within the irradiating research reactor. Test durations and post-irradiation examinations (PIEs) time lines are defined by physical processes such as the required irradiation values and required cooling times after irradiation, which cannot be accelerated. General steps in the process are as follows:

1. Definition of the experiment
    - The objectives and parameters of the experiment are defined and translated into operational requirements for the test (maximum fission density and burnup, and type and number of samples).
    - Rough estimate of the time needed: between 3 and 6 months, but potentially much longer (1 to 2 years) if no specific frame-

density LEU research reactor fuels. CERCA sells research reactor fuels to many of the HPRRs in Europe, and, as with operators worldwide, there is concern over the uncertainty in the pricing for the high-density LEU fuels. See Appendix E for a short discussion on the economics of LEU fuel from U.S. and French perspectives; the French consider high-density LEU fuel as a commercial venture, while the United States considers its LEU fuel development and fabrication as a government program "for the public good."
SOURCE: Data collected by the committee during site visits to Europe and U.S. domestic reactor sites; see Appendix C.

work or preexisting budget is available and if several partners are involved.

2. Preparation: design analysis of the experiment and production of the samples
   - Analysis such as neutron or thermodynamic analyses of the proposed testing configuration and experimental conditions have to be performed and submitted to the authority in charge of the safety of the reactor.
   - In parallel, samples (mini-plates or full-sized plates[20]) have to be produced and characterized.
   - Rough estimate: between 3 and 6 months for the design and the calculation of the experiment, and between 6 and 12 months for the production or manufacturing of samples, depending on the number and type of the samples (mini-plates, full-sized plates, full-sized assembly).
3. Irradiation of the samples
   - The amount of time needed for this step depends on the objective of the experiment (low or high power density, maximum burnup), the enrichment used (LEU or HEU for very high-power density experiment), and the availability of the reactor. Notably, many of the irradiation tests performed on the new fuel are performed in the research reactors slated for conversion after the fuel has been qualified (e.g., Belgian Reactor 2 [BR2] or ATR).
   - Rough estimate: 6 to 12 months (often more)
4. Cooling
   - Cooling, or the reduction in radioactivity due to natural radioactive decay, time lines of the samples depend on the type of experiment (mini-plate or full-sized assembly, for example), its activity level at the end of experiment, and the availability of a high-activity hot cell.[21]
   - Rough estimate: between 6 and 9 months
5. Post-irradiation examination
   - The time line for PIE varies widely depending on the analysis required. Some examinations, such as transmission electron microscopy (TEM), are often made 2 or more years after the end of the irradiation.

[20] Irradiation testing can be performed on various-sized plates. Full-sized plates refer to plates of the same dimension as those that will be used within research reactors. Mini-plates are smaller-sized plates so that a larger number of variations of fuel composition or cladding may be investigated during the irradiation test.

[21] A *hot cell* is a specially designed, radiation-shielded facility that allows for remote measurements and analysis of radioactively "hot" samples.

- Rough estimate: initial examination between 6 and 9 months with some examination taking place 1 to 2 years later.

6. Analysis and synthesis of results
   - Rough estimate: between 3 and 6 months

Some of the tasks listed above such as steps 1 and 2 can be performed in parallel, but others are sequential. A rough estimate for the total duration for an experiment is between 2 and 4 years. However, the details of the experiment will ultimately determine the time line (see discussion later in this chapter, e.g., Figure 4.8 for HERACLES dispersion fuel tests and Figure 4.9 for U.S. monolithic fuel test). Once testing is completed, qualification of the fuel by a specific country's and/or research reactor's regulatory body must be obtained adding approximately 1 to 3 years to the total time line. See Figure 4.1, steps 5 through 7, for a rough estimate for the U.S. regulatory time line.

Dispersion Fuel: Test Results and Future Testing

The first irradiation tests on UMo full-sized dispersion plates were performed by the French CEA in OSIRIS and BR2 reactors (IRIS-1, IRIS-2 tests in OSIRIS, and the FUTURE test in BR2) on U-7Mo (uranium alloy with 7 percent by weight of molybdenum), in a pure Al matrix, at densities ranging from 8.0 to 8.5 gU/cm^3. These tests were conducted in parallel with the first five RERTR tests on UMo dispersion mini-plates by Argonne National Laboratory (ANL) in ATR (RERTR-1, -2, -3, -4, -5) on different U-xMo dispersion fuel (with x ranging from 6 to 10 percent) in a pure Al matrix.

The IRIS-1 full-sized plate test performed on UMo ground particles was successful with an acceptable thickness increase (post-irradiation) of approximately 70 μm (see Figure 4.6) at low power densities (12 kW/cm^3 or 140 W/cm^2) and fission densities up to 4.5×10^{21} fissions/cm^3 (see Figure 4.6). These test results were consistent with those of the RERTR mini-plate tests with maximum burnup values of 80 percent and fission densities of 6.0×10^{21} fissions/cm^3 (Hofman et al., 2004a). The IRIS-2 and FUTURE full-sized plate tests performed on U-7Mo atomized particles at higher power densities (20 and 30 kW/cm^3, respectively) resulted in plate failures at fission densities lower than 2.5×10^{21} fissions/cm^3 due to excessive swelling, resulting in a sharp local increase in plate thickness (pillowing). These changes in the geometry of the plates could have impacts on the ability to adequately cool the fuel plate, potentially leading to failure of the fuel plate and contamination of the reactor.

Following IRIS-1 and RERTR tests, there was confidence in UMo qualification plans. However, the failures of the full-sized plates in the IRIS-2 and FUTURE irradiations in 2003 led to metallographic examination of

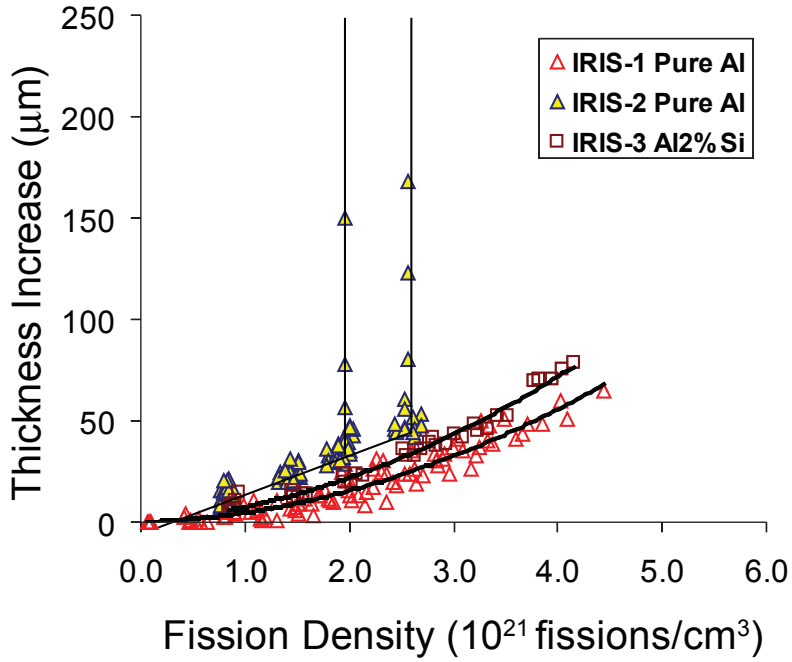

FIGURE 4.6 Results of the IRIS-1, -2, -3 tests on U-7Mo dispersion fuel. The graph shows the limited increase of the full-sized plates' thickness up to 4.5×10^{21} fissions/cm^3 in the IRIS-1 test (approximately 70 µm), the pillowing of the full-sized plates in IRIS-2, at 2.0 and 2.5×10^{21} fissions/cm^3 (local sharp increase), and the stabilization in the IRIS-3 experiment by addition of 2 percent silicon in the matrix. See text for discussion on "successful" IRIS-1 irradiation versus IRIS-2 full-plate failures. SOURCE: Modified from Lemoine and Wachs (2007).

several RERTR-4 mini-plates. It was discovered that the phenomenon that led to the failure in the full-sized plates was also evident in its early stage in the higher-power irradiations of the mini-plates (Hofman et al., 2004b). It was determined that pillowing did not occur in the RERTR tests because of the limited dimensions of the mini-plates. Furthermore, the success of the IRIS-1 test, a full-sized experiment, is attributed to two factors:

- A lower-power density (lower than IRIS-2, FUTURE, and the RERTR-4 mini-plate experiments).

- Increased resistance of its fuel meat to the pillowing phenomenon due to the morphology of the ground particles (much more jagged than the spherical atomized powder).[22]

The failure of the FUTURE experiment was determined to have been caused by large voids resulting from excessive interaction between the UMo particles and the Al matrix (Leenaers et al., 2004), leading to plate pillowing by loss of mechanical resistance of the fuel meat. To prevent this interaction, two solutions were proposed and sequentially tested. First, the addition of Si to the Al matrix was expected to reduce the rate of interaction. Alternatively, the application of a Si or ZrN coating on the UMo powder particles was expected to avoid the interaction altogether.

These proposed solutions clearly improved the behavior of UMo dispersion fuel, with successful irradiations up to 60 percent burnup (4.5×10^{21} fissions/cm^3) as shown in Figures 4.6 and 4.7 for IRIS-3 with 2 percent Si addition in the Al matrix, E-FUTURE with 4 and 6 percent Si addition, and SELENIUM with Si or ZrN coating. The fuel plates still showed a rapid increase in swelling between 4.7 and 5.0×10^{21} fissions/cm^3, which is well short of the required 6.8×10^{21} fissions/cm^3 to meet operational and safety constraints of all four European HPRRs (see Figure 4.4).

The behavior at higher fission densities is not attributed to interaction-layer (IL) formation or an effect of Si added to the matrix, because the same effect is observed in the ZrN-coated U-7Mo dispersion fuel where no Si is present and only a very limited interaction layer is formed. The current working hypothesis attributes this behavior to the swelling of UMo particles due to recrystallization (Leenaers, 2014). To mitigate this effect, the HERACLES group will test the performance of UMo fuel that has been annealed to increase its grain size and homogeneity.

The HERACLES group currently plans six additional irradiation experiments: EMPIRE, SEMPER FIDELIS, SELENIUM 2, E-FUTURE-3, and FUTURE-MONO-I and -II (see Figure 4.8). EMPIRE and SEMPER FIDELIS are sample plate experiments. EMPIRE is a mini-plate test to be irradiated in ATR, and SEMPER FIDELIS is a subsized plate test (approximately one-third of a full-sized plate) to be irradiated in BR2. The other experiments, SELENIUM 2, E-FUTURE-3 (for dispersion fuel), and FUTURE-MONO-I and -II (for monolithic) are full-sized plate irradiation experiments. Four of these test campaigns (all but the FUTURE-MONO-I and -II monolithic fuel tests) will provide data to support the qualification of the UMo dispersion

[22] The ground particles were used for IRIS-1 because it was the only available powder when the experiment was launched. However, the grinding process currently used to make U_3Si_2 powder is not a viable industrial process to produce UMo powder because UMo is much more ductile than U_3Si_2.

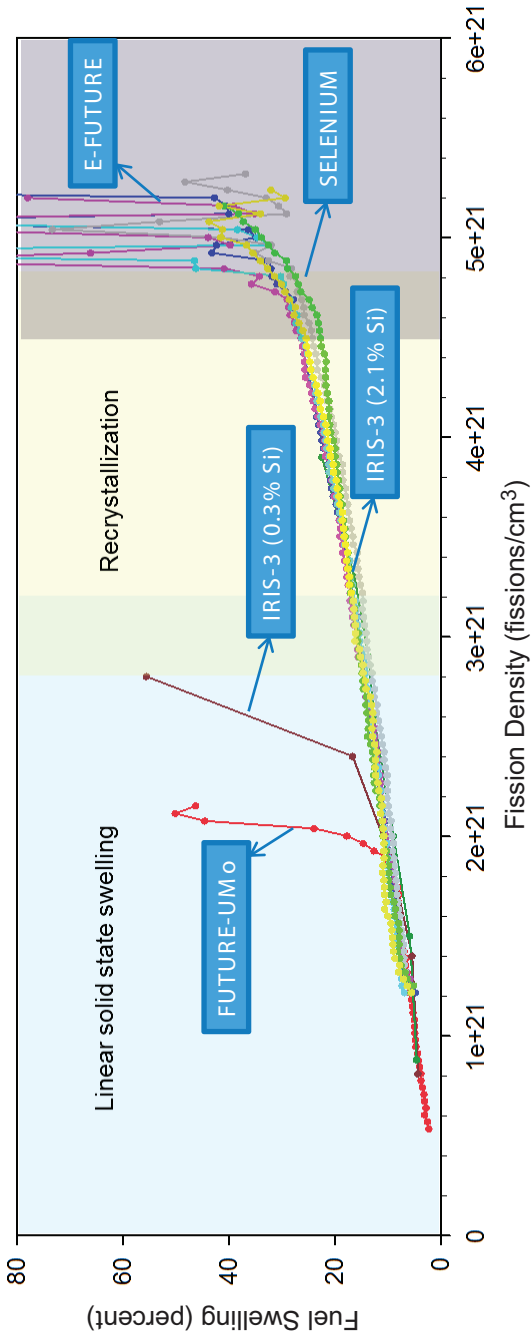

FIGURE 4.7 Results of irradiation tests performed in BR2 on U-7Mo dispersion fuel: Fuel swelling from the FUTURE, E-FUTURE (plates with 4 and 6 weight by percent silicon in the matrix) and SELENIUM (silicon and ZrN coated) experiments. SOURCE: Modified from Van den Berghe et al. (2015).

fuel up to 40 kW/cm^3 and 6.8 × 10^{21} fissions/cm^3, meeting the operational and safety envelopes for Réacteur à Haut Flux (RHF), Jules Horowitz Reactor (JHR), and BR2 (see Figure 4.4). Three of these experiments will be carried out over the next 7 years (EMPIRE and SEMPER FIDELIS, from 2016 to 2019) and the E-FUTURE-3 test will be carried out thereafter (2019–2022) before irradiation of a mixed-element[23] test may begin (see Figure 4.8). The dispersion fuel testing program extends to 2025.

The regulatory qualification of the UMo dispersion fuel will require irradiation of mixed-element and lead test assemblies in each candidate reactor prior to LEU conversion. In addition, the licensing process of the new fuel varies by reactor and regulatory body. Therefore, conversions of research reactors would occur several years after the conclusion of the testing program, assuming it is successful and there are no further delays.

In summary, the results of current irradiation experiments provide confidence that UMo dispersion fuels could be qualified for burnup below fission densities of 4.5 × 10^{21} fissions/cm^3 and up to power densities on the order of 40 kW/cm^3. These testing parameters meet both the operating envelope and safety margin requirements[24] for one European HPRR: RHF (see Figure 4.4).

Dispersion Fuel Fabrication Status and Challenges

The HERACLES consortium is also focused on UMo dispersion fuel fabrication and qualification. Irradiation experiments for dispersion fuel are mainly being conducted on full-sized plates manufactured by CERCA using industrial processes (see the lower one-third of Figure 4.8). As such, successful irradiation experiments provide data for qualification of the fuel plate manufacturing process. In addition, there is a long history of manufacturing dispersion fuels at CERCA, much of which has been already transferred to the development of the UMo dispersion fuel manufacturing process. The most important process that still needs to be fully developed at an industrial scale is the coating of the UMo particles, which is needed to prevent interaction-layer formation.

[23] A mixed element is a standard fuel assembly in which a portion of the assembly is replaced by an experimental plate. For example, a mixed element would be formed by replacing the external ring of a driver BR2 fuel assembly (six rings of three curved HEU UAlx fuel plates) with three LEU UMo fuel plates.

[24] The maximum operating envelope requirement for RHF is 2.0 × 10^{21} fissions/cm^3 but reach testing values of 4.5 × 10^{21} fissions/cm^3 to provide a safety margin.

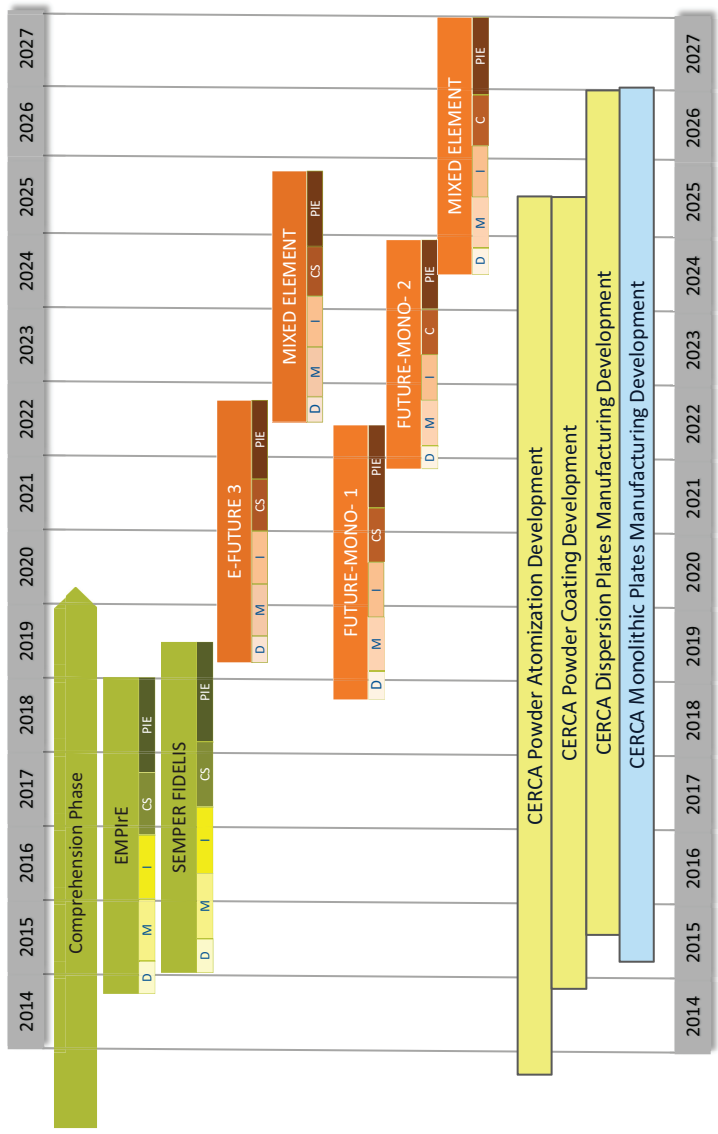

FIGURE 4.8 The HERACLES time line for UMo dispersion fuel testing (status as of Quarter 4 of 2014). Each test campaign lasts approximately 3 years and includes design (D), sample manufacture (M), irradiation (I), cooling (CS), and post-irradiation examination (PIE). The SEMPER FIDELIS and EMPIRE tests are planned to begin in 2016–2017, and the E-FUTURE-3 tests are planned to begin in 2019–2022. Not shown is the SELENIUM-2 test, which is scheduled to begin in 2019–2022. SOURCE: Breitkreutz (2015).

Russia is pursuing LEU fuel development and qualification primarily for export[25] based on a U-9Mo-Al matrix clad in Al that is extruded using traditional technology (Izhutov et al., 2013). Russia is developing dispersion LEU (UMo) fuel but is not currently developing monolithic fuel. The medium-density (approximately 5.4 gU/cm^3) LEU fuel under development is tubular (square-shaped in cross section). It is being designed for medium-flux reactors (such as MIR.M1 and Russian-supplied reactors such as the MARIA reactor in Poland). Novosibirsk Chemical Concentrates Plant (NCCP) is fabricating this new fuel. Testing of the new dispersion fuel is expected to be completed in June 2016. A conversion analysis, including a comparative safety analysis, has been completed for MIR.M1 (Izhutov et al., 2014; Mainskov, 2015). Previous studies have shown that conversion of the MIR.M1 reactor with medium-density LEU fuels (U-9Mo dispersion, 5 gU/cm^3) is feasible without loss of performance or impact to safety (Izhutov et al., 2012). However, there are no current plans to convert MIR.M1 (see Chapter 5).

A large fraction of UMo particles used in the development of the European and U.S. dispersion fuel programs were produced by South Korea (the Korea Atomic Energy Research Institute [KAERI]) using the atomization process developed for the production of the U_3Si particles of the HANARO reactor driver fuel.[26] KAERI has conducted five experiments (KOMO-1 to -5) in the High-Flux Advanced Neutron Application Reactor (HANARO) on partial- and/or full-sized UMo dispersion fuel rods with densities as high as 5 gU/cm^3 and at power densities ranging from 9 to 12 kW/cm^3. KAERI investigated many fuel parameters,[27] which confirmed the results of other international tests on the clear effect of Si on the interaction layer (Park, 2015).

In order to qualify the fuel for the new KJRR reactor, KAERI has set up an experimental program in the HANARO reactor on reduced-sized plates (Program HAMP-1, -2, -3, in progress) and two full-sized fuel assemblies planned for ATR in 2016. The first results of the HAMP-1 irradiation are consistent with IRIS-3 results (expansion of 70–80 microns at burnups to 60–65 percent). KAERI and the M^3 Office of Conversion made significant

[25] Information gathered during discussions held July 16–17, 2015, during committee site visits to RIAR in Dimitrovgrad. Costs of the fuel played a large part in Russia's fuel selection, such as the choice to produce a medium-density LEU fuel without a coating (to keep the fabrication costs as low as possible).

[26] The HANARO fuel is based on a rod-type fuel element produced by extrusion, in which the maximum volume fraction of particles is approximately 30 percent, limiting the U-loading of the U_3Si/Al dispersion fuel at the value 3.15 gU/cm^3.

[27] Parameters studied in the KOMO tests include the fuel composition of the particles (UMo binary alloys or ternary alloys as UMo-1Ti or 1Zr), the size of the particles, and the matrix composition (pure Al or Al-Si with Si addition ranges from 0.4 to 8.0 percent).

investments to successfully qualify the industrial processes to manufacture UMo dispersion fuel and qualify the UMo fuel plates for the KJRR reactor to densities of 8 gU/cm^3.

Monolithic Fuel: Test History and Status

The United States has selected monolithic UMo fuel, first proposed in the early 2000s, over UMo dispersion fuels because of its much higher uranium density (15.9 gU/cm^3 versus 8.5 gU/cm^3), which is required to meet the peak power density requirements of some of the USHPRRs (see Figure 4.3). As previously noted, monolithic fuel is fabricated by cladding a thin UMo foil with Al. The first irradiation experiments performed on mini-plates fabricated with these processes resulted in high failure rates, primarily because of the delamination of the Al cladding from the UMo foil. This behavior led to the introduction of a diffusion barrier between the foil and the cladding. A Zr barrier has proven to be successful at preventing failures at very high burnups. Experimental evidence provides confidence that UMo monolithic fuel with a Zr diffusion barrier will be qualifiable for burnups up to 8 × 10^{21} fissions/cm^3 and power density levels up to 40 kW/cm^3 (Meyer et al., 2014).[28]

The U.S. program has divided its fuel development and qualification effort into "base fuel" and "complex fuel" programs, both of which will use the same basic UMo monolithic fuel. The base fuel program, which would meet the needs of five of the USHPRRs—Massachusetts Institute of Technology Reactor (MITR-II), University of Missouri Research Reactor (MURR), Neutron Beam Split-core Reactor (NBSR), and ATR including ATR-Critical Facility (ATR-C)—has two upcoming mini-plate irradiation campaigns, MP-1 and -2, planned to start in 2018 and end in 2022 (see Figure 4.9). The first irradiation of full-sized plates for the base fuel, FP-1, will begin in 2021 and end in late 2022. Demonstration fuel assemblies specific to each reactor will be tested from 2022 through 2024.

The complex fuel program, which is focused on HFIR fuel only, faces significant additional fabrication challenges and is therefore proceeding on a different schedule. Mini-plate experiments for the complex fuel are scheduled to be conducted in 2018 and 2022, with the first full-sized plate experiments scheduled for 2023. Additional full-plate irradiation experiments will be conducted in 2026 prior to a demonstration assembly for the complex fuel in 2028. The majority of these tests will be conducted at ATR, with some fuel assembly testing occurring in BR2.

[28] These values include a safety factor because 8 × 10^{21} fissions/cm^3 is an approximate value for the maximum possible burnup (100 percent) of LEU fuel.

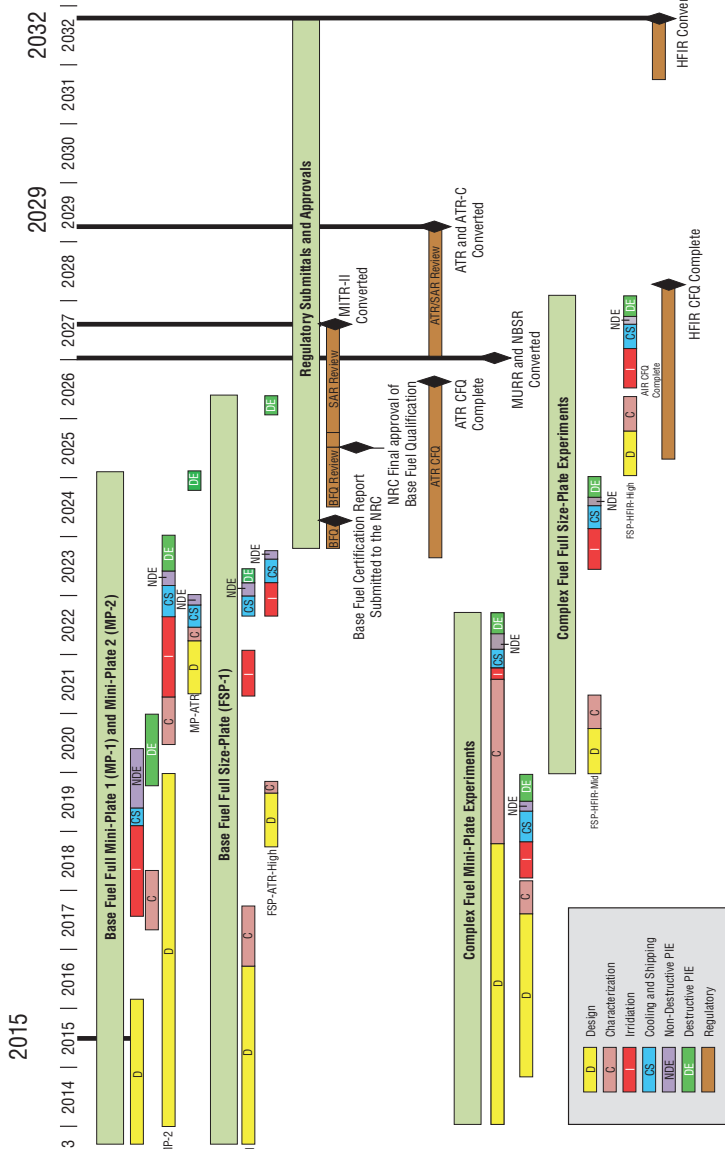

FIGURE 4.9 The roadmap for U.S. UMo monolithic fuel development, qualification, and USHPRR conversion, last updated in June 2015. Test campaigns are split into base fuel and complex fuel testing. Steps in the process are design (D), fabrication (F), characterization (C), irradiation (I), cooling and shipping (CS), nondestructive PIE (NDE), and destructive PIE (DE). SOURCE: Modified from "USHPRR Road Map_07292015.pdf" (Landers, 2015), used with permission from the National Nuclear Security Administration (DOE).

Monolithic Fuel Fabrication Status and Challenges

The fabrication process for monolithic UMo fuel presents many technical challenges. The manufacturing process has both more and different processing steps than are needed for existing dispersion fuels. These factors may well affect the relative cost of the two fuel types. The monolithic fuel manufacturing process has not yet been demonstrated as economically viable at an industrial scale.

The base fuel is a U-10Mo monolithic fuel with a Zr diffusion barrier clad in Al alloy formed via co-rolling and hot isostatic pressing processes. The current fabrication method begins by covering a cast and machined ingot of U-10Mo alloy on both sides with Zr. This is placed into a steel frame, covered on top and bottom by steel sheets, and welded closed to make what is referred to as a "can" (to prevent oxidation during the following steps). This can is hot-rolled to bond the Zr to the UMo and to reduce its thickness to the approximate required dimensions.

The foil is removed from the can, cold-rolled to the desired thickness, and cut to desired lateral dimensions. This dimensioned foil is placed into a box of Al alloy and covered by a plate of Al alloy to encase the fuel foil and diffusion barrier. Several of these assemblies are stacked with separating layers and sealed into a stainless steel can for hot isostatic pressing to bond the layers of the fuel plate. Afterwards, the plates are removed from the stainless steel can and finally cut or machined to final size.

Operators of three USHPRRs made significant changes to their fuel designs in order to simplify LEU monolithic fuel manufacturing: MITR-II, ATR, and ATR-C. MITR-II operators have agreed to remove cooling "fins" from the fuel elements after modeling and neutronic analysis showed little impact to the safety of operations. The fuel design for ATR and ATR-C originally included a burnable absorber integrated within the fuel plates, but analysis of a new LEU fuel design showed that it is feasible to move it from within the fuel plate. These are good examples of flexibility of operators with assistance from the M^3 Office of Conversion to find solutions for conversion.

The base fuel fabrication process cannot be used for the manufacture of the HFIR fuel assembly because the fuel plate is curved in a noncylindrical shape,[29] the fuel meat within the plate has variable thickness, and burnable poisons are included (see Figure 4.10). New fabrication concepts are being considered that include shaped rolls to taper the sides of the plate and extrusion of the fuel through a die of the proper cross section. Some initial studies are under way, but few results are available (Itamura, 2015; Landers, 2015; Chandler et al., 2013).

[29] The fabrication of each plate to its final shape requires skilled hand-craftsmanship.

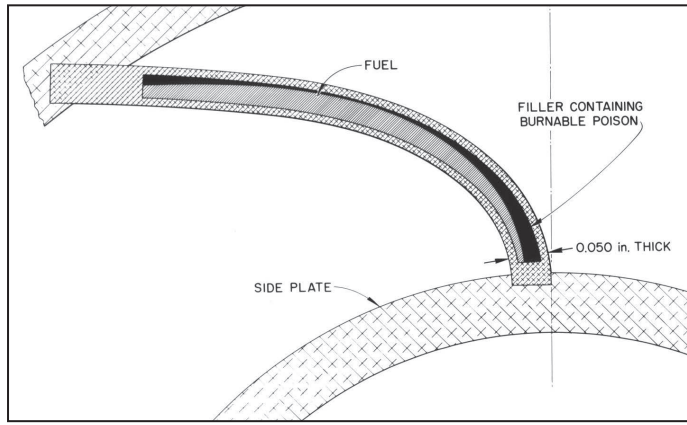

FIGURE 4.10 HFIR fuel plate: a cross-sectional drawing of the current design of an HFIR inner fuel plate. Note the nonrectangular shape of the fuel meat and the burnable poison. SOURCE: Courtesy of Oak Ridge National Laboratory.

The USHPRR fuel development roadmap in Figure 4.9 indicates that complex fuel fabrication begins in early 2017. If successful, then this will be the first monolithic fuel qualified for use in research reactors worldwide. It is clear, however, that manufacturing this fuel will be considerably more complicated, and presumably more expensive, than the base monolithic fuel.

Economics of Monolithic Fuel Fabrication

The program to develop, fabricate, and manufacture LEU monolithic fuel plates and elements has progressed much more slowly than envisioned at the outset of the GTRI effort in 2004 (Staples, 2005; Travelli, 2004). Furthermore, the manufacturing process will require additional and qualitatively different steps than dispersion fuel fabrication and is not yet optimized.

Babcock and Wilcox Technologies (BWXT) is the U.S. manufacturer of research reactor fuel. It has compared estimates of the costs for element fabrication with monolithic fuels to the costs for fabrication of the current HEU elements. These estimates assume that the yield of fuel foils is 88 percent and the yield of plates is 90 percent, the same yields currently achieved for HEU fuel (Argon, 2015). These yields have not yet been demonstrated for monolithic fuel.

A cost model was developed in 2012 to estimate the relative percentage increase in cost of fabrication of LEU fuel plates compared to the currently fabricated HEU plates. Notably, the model does not include the following:

- The cost of the cast U-10Mo received for processing (and therefore also excludes the cost of scrap associated with making the U-10M ingot).
- The cost of incorporation of any burnable absorbers (as will be needed, potentially, for HFIR fuel).
- Shipping costs.
- Waste costs.
- Any costs related to the transition from HEU plate production to LEU plate production.

The model was refined in 2014, taking into account the extended schedule for manufacturing the elements and new estimates of labor hours associated with the fabrication of plates from different coupon sizes. The resulting estimated changes in fuel fabrication costs are shown in Table 4.2. When viewing this table it is important to bear in mind that steps in the manufacturing process have not yet been finalized, leading to additional uncertainty in the overall relative costs of LEU fuel assemblies. Finally, questions remain about the fabrication of complex fuel for HFIR, arising particularly from the need to taper the foils and to incorporate burnable poisons into the fuel assemblies.

Two USHPRRs account for over 80 percent of BWXT's research reactor fuel commercial volume. Orders for ATR and HFIR fuel assemblies are responsible for approximately one-half and one-third, respectively, of the current fuel fabrication activities for the USHPRRs (Meyer, 2006).[30] The high volume of fuel utilization allows the fixed costs of USHPRR fuel manufacture to be spread over a larger number of total fuel plates than would be possible in the absence of these two reactors.[31] In short, the future demand for LEU fuel assemblies for HFIR and ATR are expected to drive the economics of LEU fuel assemblies for the remaining USHPRRs. Without a qualified fuel for HFIR and ATR, the cost per fuel plate for the remaining three USHPRRs would be expected to increase dramatically. By contrast, if one or two of the other three USHPRRs were to employ a different fuel type, then it would not have a substantial cost impact on the other reactors (assuming they would be relying on monolithic fuel).

[30] The HPRRs use (or plan to use) HEU fuel. The average annual amount of HEU feedstock at 93 percent ^{235}U assay supplied to domestic, non-DOE reactors (MITR-II, MURR, and NBSR) over the past 10 years is approximately 20 kgU per year; this amount increases to approximately 210 kgU with the inclusion of DOE reactors (ATR, ATR-C, and HFIR). For foreign research reactors and isotope production customers (e.g., AECL-Canada, BR2 and IRE in Belgium, NRG in the Netherlands, RHF-ILL in France), the average annual amount, over the same 10-year period, is approximately 52 kgU at 93 percent ^{235}U assay.

[31] Written correspondence, Gunes Argon, August 5, 2015.

TABLE 4.2 BWXT Fabrication Cost Estimates for U-10Mo Monolithic Fuel Assemblies for the USHPRRs

Reactor	2012 Estimate of Cost Increase over HEU (%)	2014 Estimate of Cost Decrease over 2012 Estimate (%)	Calculated 2014 Estimate of Increase over HEU (%)
ATR	17	15	–1
HFIR	115[a]	16	81
MITR-II	13	16	–5[b]
MURR	49	14	28
NBSR	60	25	20

[a] Because of the complex geometry of the HFIR fuel and the lack of manufacturing development to date, it is roughly estimated that HFIR foil manufacturing will take twice as long as the current manufacturing process.
[b] The decreased projected cost for MITR-II fuel assemblies may be due to simplification in its fuel assembly design. There are large uncertainties in the values of these numbers (see text for more details).
SOURCE: Data from Argon (2015).

The decision to develop monolithic UMo fuel has introduced a number of manufacturing challenges, particularly the following:

- Whereas dispersion fuels makes it possible to achieve different uranium densities by incorporating different volumetric fractions of fuel powder in the matrix (up to a practical limit), monolithic foils have a fixed uranium density. Similar design goals can be achieved by varying the thickness of the UMo foils in the monolithic plates.
- The manufacturing of monolithic fuel plates, including thin foils, barrier layers, and cladding, poses novel challenges compared to existing reactor fuels for even the basic fuel configuration and more extreme challenges for the complex fuel required by HFIR.
- Given the increased complexity in the manufacturing processes required for monolithic fuel, the yield assumptions being used in estimating fuel costs, at least initially, are likely to be overly optimistic.

ASSESSMENT OF PROGRESS TO DEVELOP LEU FUEL

The previous sections have discussed worldwide fuel development programs, including UMo dispersion and monolithic LEU fuels. Table 4.3 summarizes the committee's conclusions regarding the progress toward delivery of a variety of high-density LEU fuels, including the key steps of

TABLE 4.3 Assessment of Availability of Committee-Selected LEU Fuels

	U_3Si_2 4.8 gU/cm^3	U_3Si_2 5.8 gU/cm^3	UMo (Dispersion) Low Power Density (<17 kW/cm^3)	UMo (Dispersion) High Power Density (>17 kW/cm^3)	UMo (Monolithic)
Fuel qualification: Has the LEU fuel been qualified under irradiation? Y = yes, N = no	Y	N	[a]	N	N
Manufacturing qualification: Has the manufacturing process for the LEU fuel been qualified? Y = yes, N = no	Y	[b]	N	N	N
Commercial availability: Is the LEU fuel commercially available? Y = yes, N = no	Y	N	N	N	N
Fuel Availability: How many years to deliver LEU fuel? Rough estimate of number of years provided	< 5	5–10	5–10	15–20	15–20
Uncertainty: What is the uncertainty in the estimate of years?	Low	Medium	Medium	Medium-High	High

[a] To be confirmed by the irradiation of South Korean fuel elements in ATR.
[b] Would have to be confirmed by additional R&D program.
NOTES: Colors highlight technical risk and uncertainty associated with each fuel with red = highest risk and green = lowest risk. The uranium silicide fuel with uranium density 4.8 gU/cm^3 assumes approximately 42 percent volume of dispersant in the matrix; a uranium density 5.8 gU/cm^3 assumes approximately 50 percent volume of dispersant in the matrix.
SOURCE: Developed by the committee from multiple sources.

fuel qualification, manufacturing qualification, commercial availability, and the expected schedule for fuel availability. The values in the table indicate that silicide fuel (U_3Si_2) is the most promising fuel that could potentially be qualified in less than 5 years. Because the South Korean program is focused on the qualification of UMo dispersion fuel at low power density (below 185 W/cm^2 or 17 kW/cm^3), the committee has separated this fuel from the "high" power density UMo dispersion fuel, which satisfies the usual HPRR power density-burnup envelope.

This assessment leads to the following findings:

Finding 6: Most of the technical challenges to converting the remaining research reactors to low enriched uranium (LEU) concern a few high performance research reactors (HPRRs) that require a new high-density LEU fuel to be developed and qualified.

a. The timescale for designing, fabricating, qualifying, and converting to UMo LEU monolithic (U.S. program) or dispersion (European program) fuel for all HPRRs is now estimated to be around 15–20 years, resulting in nearly two decades of continued reliance on weapon-grade highly enriched uranium (HEU).

b. The monolithic fuel faces more manufacturing challenges for qualification and therefore higher uncertainty and risk in the estimate of the time line.

Finding 7: The economic viability of high-density low enriched uranium fuel is highly uncertain and is a source of significant concern to the operators of high performance research reactors worldwide.

Summary of the Current Status of Conversion

The "principles of conversion" defined and supported by U.S. conversion programs since 1978 lead to constraints on the design of the LEU fuel as described previously: for example, the amount of ^{235}U that LEU fuel assemblies must contain, their geometry and size, and the operational envelopes over which they must perform safely. One of the critical parameters for an LEU replacement fuel is uranium density. Many reactors have converted without significantly affecting their performance using LEU fuels with densities up to 4.8 gU/cm^3. However, the highest-performing research reactors throughout the world cannot convert using these fuels while maintaining their performance. New very high-density LEU fuels have been developed for these reactors, but they are not yet qualified. The fuels (UMo dispersion and monolithic) did not pass initial irradiation tests over their full operating envelopes, failing at fission densities of 2.0 to 2.5 × 10^{21} fissions/cm^3

(see FUTURE-UMo results in Figure 4.7). Investigation and determination of the root causes of the failures and identification of solutions have taken more than a decade of research and additional testing. The current estimates to qualify the UMo monolithic base and complex fuels are 12 and 13 years, respectively. Conversion of USHPRRs occurs several years later (after regulatory approval) and is estimated to occur in 2029 (for completion of the USHPRRS using base fuel) and 2032 (for HFIR).[32] In other words, shipments of 93 percent HEU fuel will be required for the next approximately 15–20 years to supply the USHPRRs. Furthermore, although the new fuels are expected to, at least initially, be more expensive than existing fuels, no comprehensive cost analysis has been performed because of large uncertainties in important parameters, including specification of the manufacturing process.

ACCELERATING THE MINIMIZATION OF WEAPON-USABLE NUCLEAR MATERIAL

With the performance constraints defined above and the schedules for conversion now stretching nearly two decades into the future, the committee felt compelled to investigate the opportunities to meet M[3]'s primary objective of "achieving permanent threat reduction by minimizing and, when possible, eliminating weapons-usable nuclear material around the world."[33] These opportunities arise from relaxing the constraint on LEU enrichment.[34] Box 4.2 provides background on the proliferation and security risks associated with enrichments higher than 20 percent but well below weapon grade.

Several sources were used to provide rough estimates of the minimum enrichment required to allow conversion of each HPRR using different fuel systems. The quality of the estimates varies across the suite of HPRRs because of differing types of information collected by the committee. The results of the analysis are shown in Table 4.4.

Qualified silicide (U_3Si_2) fuel, as-yet-unqualified higher-density U_3Si_2 fuel, and UMo dispersion fuel were considered for each USHPRR, either as a path to conversion earlier than currently scheduled or as a backup option to mitigate the risks in monolithic fuel development and fabrication.

[32] USHPRR Roadmap, provided to the committee by DOE/NNSA in January 2015 and (updated) August 2015 (Landers, 2015).

[33] See http://nnsa.energy.gov/aboutus/ourprograms/dnn/m3.

[34] The relaxation of performance constraints has been considered by the M[3] Office of Conversion and operators to some extent. Examples of successful implementation of adjustments to performance constraints are increased operational power post-conversion to compensate for LEU performance impacts (HFIR), increased experimental capabilities (NBSR), or changes to fuel element design to ease manufacturing (MITR-II).

BOX 4.2
Uranium Enrichment Level, Weapon Usability, and Proliferation-Risk Attributes

Critical mass is a good, first-order indicator for the attractiveness of enriched uranium for use in a nuclear weapon or explosive device. As shown in Figure 2.1, the critical mass drops sharply as the enrichment (i.e., the concentration of ^{235}U in the material) increases and fewer neutrons interact with nonfissile ^{238}U. The critical mass of 45 percent enriched uranium is 3–4 times higher and the critical mass of 20 percent enriched uranium is 12–15 times higher than 90 percent enriched uranium (weapon grade).

In addition to the amount of material needed to reach criticality, and as a compounding effect, the critical mass value can also serve as a simple indicator of the difficulty of rapidly assembling the device (which has to happen on the order of milliseconds for a uranium-based gun-type device). In general, acceleration scales inversely with mass (Glaser, 2006). Therefore, the increase in mass as enrichment decreases both weakens the chain-reacting properties of the material when it is in its final (supercritical) configuration *and* increases the level of difficulty of achieving this configuration. Combined, this explains why uranium enriched to less than 20 percent is considered non-weapon-usable.

To obtain a slightly more robust assessment of the weapon usability of enriched uranium, one can refer to the original memorandum prepared by the U.S. Atomic Energy Commission to establish the 20 percent limit for uranium that would be exported to foreign countries for use as research reactor fuel (Hafstad, 1954). The report uses a simple expression to estimate the amount of enriched uranium (M) needed to achieve the same reference yield (of 1 kiloton) in a nuclear explosive device as a function of the ^{235}U concentration (ε) in the material:[a]

$$M(\varepsilon) \sim \frac{1}{\varepsilon^{1.7}}$$

This expression can be used to estimate the relative increase of the amount of less-enriched uranium needed when compared to weapon-grade highly enriched uranium (W-HEU):

$$\frac{M(0.45)}{M(0.93)} = \left(\frac{0.93}{0.45}\right)^{1.7} \approx 3.4 \text{ and } \frac{M(0.20)}{M(0.93)} = \left(\frac{0.93}{0.20}\right)^{1.7} \approx 13.6$$

In other words, a device based on 45 percent enriched uranium requires approximately 3.4 times more material, and a device based on 20 percent enriched uranium requires approximately 13.6 times more material when compared to a device using W-HEU. This is almost perfectly consistent with the simple comparison of critical masses above.

For a more realistic assessment of the proliferation and security risks associated with research reactor fuel, these ratios ought to be weighted, however, by the amount of uranium needed to fuel a given reactor over the same period of time. A research reactor using less-enriched uranium requires more fuel and, to a first approximation, the ^{235}U consumption remains about the same for equal power levels; for example, the fuel throughput at least doubles if the enrichment is halved.

continued

BOX 4.2 Continued

TABLE B4.2 Quantifying Proliferation Risks of Research Reactor Fuels with Reduced Enrichment

Enrichment (%)	Mass Ratio A (for Explosive Device)	Mass Ratio B (Fuel Throughput)	"Risk Metric" (B/A)
93	1	1	1
45	~3.4	~2.0	~0.59
27	~8.2	~3.3	~0.40
20	~13.6	~4.4	~0.32

SOURCE: Data from Glaser (2006, pp. 1–24).

For an assessment of the net gain in proliferation resistance for every enrichment level considered, one can use the relative increase in fuel demand divided by the mass ratio for an explosive device. Table B4.2 summarizes the basic results. Very roughly, a reduction of the fuel enrichment from 93 percent to 45 percent cuts the attractiveness by about 40 percent, and a reduction from 93 percent to 20 percent cuts the attractiveness by almost 70 percent, compared to W-HEU. Put differently, and perhaps not too surprisingly, use of 45 percent enriched fuel is roughly equivalent to getting "half way" compared to a full conversion to 20 percent enriched material.

As the enrichment level is reduced, the amount of material needed for one nuclear explosive device increases significantly (Mass ratio A). At the same time, however, more fuel is needed to operate the same reactor (Mass ratio B). The ratio of both numbers provides a simple metric (a "risk metric") to compare proliferation-risk attributes of different fuel enrichment levels: 45 percent enriched fuel offers a 40 percent reduction, and 20 percent enriched fuel offers a 70 percent reduction, compared to weapon-grade fuel (93 percent U^{235}). Recall that the DOE material attractiveness analysis (from the perspective of an adversary) assigns a lower value of attractiveness for 50 percent or lower enrichment. This simple analysis does not account for the difficulty of using less-enriched fuel in a nuclear explosive device. Below an enrichment level of 20 percent, the use of uranium for weapon purposes is considered impractical.

[a] The memorandum does not explicitly distinguish implosion-type from gun-type devices, but the absolute numbers given are apparently for an implosion-type design. Here, we assume the mass-enrichment dependency for constant explosive yield remains approximately valid for both designs.

TABLE 4.4 Approximate Enrichments Necessary to Allow Conversion from W-HEU to Lower Enrichments

HPRR	U_3Si_2 4.8 gU/cm^3 (%)	U_3Si_2 5.8gU/cm^3,[a] (%)	UMo (Dispersion)[b] (%)	UMo (Monolithic)[b]	Years to Conversion Using UMo (Monolithic) Fuel[c]
ATR	35–40[d]	~30	25–30	LEU	14 years
HFIR	35–40[d]	~30	25–30	LEU	17 years
NBSR	~25[d]	LEU	LEU	LEU	12 years
MURR	~45[d]	~40	~35	LEU	12 years
MITR-II	~35[d]	~30	20–25	LEU	12 years
FRM-II	50–60[e]	35[f]	30	LEU	N/A
BR2	~27[e]	~22	LEU	LEU	N/A
JHR	27[e]	22	LEU	LEU	N/A
RHF	~27[e]	~22	LEU	LEU	N/A

[a] Enrichment for 5.8 gU/cm^3 fuel was estimated by the following ratio: [(4.8/5.8) × (enrichment)] to preserve ^{235}U density.
[b] A factor of 0.85 applied to account for reactivity loss of UMo versus U_3Si_2 fuel.
[c] Chris Landers, USHPRR Road Map—June 2015.
[d] Matos (1996).
[e] The 60 percent estimate is based on the required ^{235}U inventory in the core. FRM-II operators have recently begun exploring options to increase the available fuel volume, which might enable enrichment levels closer to 50 percent. The entries for BR2, JHR, and ILL are estimated on the basis of comparisons with FRM-II.
[f] This value assumes U_3Si_2 fuel at 6 gU/cm^3 with extended fuel volume (Pichlmaier et al., 2015).

In addition, consideration was given to the possibility that dispersion and/or monolithic fuel could be qualified for reduced performance envelopes appropriate for some of the USHPRRs. This analysis was based on existing experimental evidence and further experimental results anticipated in the near future. The committee estimated the enrichment levels and number of years that might be necessary to complete fuel qualification and reactor conversion analysis. Although these estimates are approximate, they indicate the kind of analyses that could guide risk mitigation for the M^3 Office of Conversion.

The committee used information from a study by Matos (1996) in its analysis. Matos estimated the uranium density required to meet the performance goals of USHPRRs using U_3Si_2 fuel. This uranium density was converted using a simple mass ratio (see discussion earlier in this chapter) to estimate the enrichment that would satisfy performance constraints for the

HPRRs. The committee estimated that it could take up to 5 years to complete new safety analyses and confirm reactor performance/conditions for conversions using already-qualified U_3Si_2 fuel with a density of 4.8 gU/ cm^3. Despite this lead time, U_3Si_2 fuel is well understood, and the uncertainties and risks associated with using this fuel are expected to be minimal. Previous analysis for JHR has determined the necessary enrichment above LEU levels to satisfy performance requirements; this level of enrichment is used as a surrogate for RHF and BR2 (see notes for Table 4.4).

Next, the committee assumed that a slightly higher uranium loading was possible (5.8 gU/cm^3) for U_3Si_2 fuel and determined a new minimum enrichment level following a similar analysis (see Table 4.4). The committee estimated that it would take 5 to 10 years to demonstrate that such a fuel could be qualified. Assuming such fuel would successfully pass irradiation testing in full-plate form, the risks associated with its manufacture are estimated to be low.

For UMo dispersion fuels with a uranium loading of 8 gU/cm^3, two time lines were considered. The accelerated time line is based primarily on the current South Korean development program that aims to have a fuel that would be qualified for low-power-density reactors (less than 17 kW/cm^3) within 10 years. Such a fuel would be suitable for NBSR (Hanson and Diamond, 2014) and might be suitable for MITR-II. On the other hand, the European program has demonstrated performance of a UMo dispersion fuel for higher power density (greater than 17 kW/cm^3) and low burnup that might be suitable for RHF. For other European HPRRs, the successful completion of the entire UMo dispersion fuel development program is necessary. Even then, such fuel would only be suitable for NBSR and possibly MITR-II in the United States, with no, or perhaps only marginal, acceleration of the conversion time line possible over what is projected with monolithic fuel.

For UMo monolithic fuel, the U.S. development program intends to convert the USHPRRs with the lowest power densities (MITR-II or NBSR) 2–5 years before the remaining reactors. The experimental evidence already obtained provides high confidence that the fuel will be able to meet the performance envelopes of MURR, MITR-II, and NBSR. For each of the LEU fuels given in Table 4.3, the committee has estimated the enrichment that would allow each of the HPRRs to operate within its performance (reactivity) constraints (see Table 4.4). The entries are based on the simple mass ratio model explained in Box 4.2 and do not account for important details such as thermal hydraulic/safety limits or detailed flux/power distributions.

DECREASE IN WEAPON-GRADE HEU THROUGH USE OF NON-WEAPON-GRADE HEU

Table 4.4 indicates that all HPRRs with the possible exception of FRM-II can be converted to interim enrichment levels of 30–45 percent with currently qualified and commercially available U_3Si_2 fuel (4.8 gU/cm^3). A more detailed design and analysis effort would ensure that the non-weapon-grade HEU fuel assemblies would meet all the requirements for conversion (including licensing requirements) of each reactor.

Table 4.5 shows the resulting decrease in the amount of weapon-grade HEU (W-HEU) that would be shipped while awaiting the development of suitable UMo LEU fuel (i.e., monolithic UMo fuel for the USHPRRs and FRM-II and dispersion UMo fuel for the European HPRRs). The entries in this table are estimates based on Tables 4.3 and 4.4 and the assumption that, if U_3Si_2 fuel (4.8 gU/cm^3) is used, all reactors could convert in 5 years. These approximate calculations suggest that the potential reduction in W-HEU shipments (more than 3 tons of weapon-grade material over the next 17 years) warrant consideration of the non-weapon-grade HEU alternative.

TABLE 4.5 Reductions in Civilian W-HEU with Interim Conversions of HPRRs

HPRR	Years to Conversion (YTC) with High-Density LEU Fuel[a]	Years without W-HEU Shipments (Interim Conversions)[b]	W-HEU Shipped/Year (kg)	Total W-HEU Usage Avoided (kg)
ATR	14	9	120	1,080
HFIR	17	12	80	960
NBSR	12	7	13	91
MURR	12	7	24	168
MIT	12	7	8	56
FRM-II	17	12	38	456
BR2	12	7	29	203
JHR	0	0	0	0
RHF	12	7	55	382
Total[c]				3,399

[a] Office of Conversion estimates for USHPRRs and committee estimates for European HPRRs.
[b] Years to conversion with qualified U_3Si_2 fuel is estimated to be 5 years.
[c] Excluding W-HEU shipped to JHR which has not yet begun operations.
SOURCE: Data from Meyer (2006).

Several important points emerge from the foregoing discussion and analyses:

1. HPRRs need very high-density LEU fuels to maintain an adequate number of ^{235}U atoms per volume of fuel so as to convert without degrading performance.
2. Preliminary studies performed around 2000 resulted in the selection of the UMo alloy as the best candidate by the United States. Many other nations with very high-density fuel development programs agreed with this choice. Work continues on two kinds of UMo fuel: a dispersion form similar to currently available fuels and a monolithic form proposed by U.S. developers.
3. Both of these fuels have encountered problems during irradiation testing. Various improvements have been implemented by fuel designers to address these problems, but the qualification of the fuels and eventual conversion of the USHPRRs is anticipated to take another 12 to 17 years. It is difficult for reactor operators to take seriously deadlines this far into the future. Reactor operators accept but are not seriously planning for conversion, just as they are committed to relicensing in 20 years but may not start planning for it until approximately 10 years in advance.
4. The committee explored the implications of using a well-known, qualified, and widely used fuel (U_3Si_2 at 4.8 gU/cm^3) enriched to levels above 20 percent but well below weapon grade to compensate for its insufficient density. The exact enrichment value for each HPRR would need to be determined by additional studies. Such an interim conversion step would avoid the use of W-HEU by HPRRs for the next 10 to 20 years.
5. The committee estimates that most of the HPRRs could be converted to this fuel in less than 5 years,[35] which would avoid the shipment of more than 3 tons of W-HEU over the course of about 17 years.

Finding 8: UMo dispersion fuels might be suitable for the conversion of some USHPRRs (e.g., NBSR and MITR-II). The fuel being qualified by South Korea may offer modest acceleration in the anticipated conversion time line for this subset of U.S. research reactors. Even without reduced time lines, the dispersion fuels being developed by South Korea and the European consortium known as HERACLES can be used to mitigate the technical risk that remains in the current U.S. monolithic fuel development time line.

[35] Because this fuel is commercially available, no additional manufacturing development is necessary. However, fabrication lines may need to be restarted.

Finding 9: High performance research reactors (HPRRs) could operate without reduction in either performance or cycle length with currently qualified silicide fuels at enrichments that exceed 20 percent but are significantly lower than weapon-grade HEU (90 percent or greater). Calculations performed for the European HPRRs (FRM-II, ILL, and JHR) have assessed the feasibility of this option, but similar assessments do not exist for the HPRRs in the United States.

Recommendation 2: Despite a timescale that is now understood to be much longer than initially expected, the United States should continue to develop a very high-density, low enriched uranium (LEU) fuel to convert as soon as possible the existing generation of U.S. high performance research reactors to LEU operation as well as to enable a new generation of research reactors.

Recommendation 3: The United States should closely monitor the development of low enriched uranium (LEU) dispersion fuels (e.g., in Europe, South Korea, and Russia) and evaluate their possible use as backup options for U.S. high performance research reactor conversions if there are unexpected delays in the development of the U.S. monolithic fuel.

Recommendation 4: To achieve the goal of using as little highly enriched uranium as possible during the many years that it will take to design and qualify appropriate low enriched uranium (LEU) fuel, the United States should pursue an interim solution that reduces the civilian use of weapon-grade material.

- **a. During this interim period, high performance research reactors should use dispersion silicide fuel enriched to the lowest practical level, which can be produced with technologies already known to be reliable. The precise enrichment level can be quickly determined by a focused, small-scale study.**
- **b. The United States should downblend the remaining 20 metric tons of highly enriched uranium (HEU) designated for civilian research reactor use to this lowest practical enrichment level as soon as it has been determined.**
- **c. The interim solution should be pursued in a way that does not compromise the long-term goal of eliminating HEU usage in civilian applications.**

The committee recognizes that relaxing the constraint of 20 percent enrichment is a complex policy decision involving many stakeholders. Although a relaxation of the 20 percent enrichment threshold may be per-

ceived as undermining a commitment to eliminating civilian HEU use, it permits other actions, namely the rapid conversion of reactors away from weapon-grade enrichment levels and the permanent downblending of HEU stocks to much lower enrichments.

The committee further recognizes the additional cost and licensing risk with the proposed stepwise conversion, but it notes that the alternative is to "do nothing" for two decades. The reactor operators may prefer this solution. With stepwise conversion the operators will face conversion within a much shorter time line and the potential for two (instead of one) conversions. Doing so may well bring to focus decisions that are required for any conversion and may precipitate innovations beyond any this committee recommends.

By clearly indicating such actions as an interim solution, this approach should in no way hinder or delay qualification of the very high-density LEU fuel.[36] Furthermore, it would emphasize the continuing U.S commitment to reducing the risk associated with civilian use of HEU through actions that can be undertaken immediately.

[36] The U.S. Nuclear Regulatory Commission issued a conversion regulation in 1986 (10 CFR § 50.64) that states that replacement of HEU fuel with LEU fuel acceptable to the Commission should take place in accordance with an approved schedule and that acquisition of additional HEU fuel will not be initiated if LEU "fuel acceptable to the Commission" is available (unless the reactor has a unique purpose). Therefore, it is important that the high-density LEU fuel development and qualification proceed in parallel with the stepwise conversion.

5

Nontechnical Obstacles to Reactor Conversion

This chapter identifies key nontechnical obstacles to converting the remaining HEU-fueled research reactors and suggests steps that could be taken to overcome the identified obstacles. The chapter includes examples in which nontechnical factors dominate the decisions to convert and the actions required for conversion.

The conversion of civilian research reactors from highly enriched uranium (HEU) to low enriched uranium (LEU) fuel, or the decision to shut down HEU-fueled research reactors, depends at least as much upon financial, organizational, diplomatic, and political factors as upon technical factors. Several of the conversion steps discussed in Chapter 4 require actions and decisions that are primarily nontechnical, beginning with agreement by a host country to consider conversion of one or more of its research reactors. The priority given to HEU reduction by a host country determines the resources for and the speed of the conversion process; and different countries (and interest groups within countries) prioritize such minimization very differently. In the United States, for example, conversion is given high priority and support by Congress and presidential administrations (see Chapter 2), and yet the United States has one civilian research reactor for which the obstacle to conversion is nontechnical as noted in this chapter. In Europe, there is widespread support for conversion to LEU once a qualified fuel becomes available.[1,2] In Russia, however, minimizing HEU usage in its domestic civilian research reactors is not a high priority.

[1] For example, for HFR conversion, see http://www.emtr.eu/hfr.html; for BR2 conversion, see http://www.igorr.com/home/liblocal/docs/Proceeding/Meeting%2012/session%200/IGORR09-Beijing-EK-rev3.pdf.

[2] Multiple presentations and discussions during site visits to European facilities; see Appendix C for a full listing.

NONTECHNICAL OBSTACLES TO REACTOR CONVERSION IN THE UNITED STATES

Eight research reactors in the United States operate with HEU fuel. Seven of these reactors are high performance research reactors (HPRRs): Advanced Test Reactor (ATR), ATR-Critical Facility (ATR-C), University of Missouri Research Reactor (MURR), Massachusetts Institute of Technology Reactor (MITR-II), High Flux Isotope Reactor (HFIR), Neutron Beam Split-core Reactor (NBSR), and Transient Reactor Test Facility (TREAT[3]). These reactors require a new fuel to be developed and qualified before conversion can take place and, as discussed in Chapter 4, fuel development is a technical obstacle to conversion. However, one U.S. civilian research reactor—the General Electric Nuclear Test Reactor (GE-NTR) in California—continues to operate with HEU uranium-aluminum (U-Al) alloy fuel. It is technically possible to convert this reactor with existing LEU fuel (NRC, 2012). Until recently, however, and despite strong political support and available resources for conversion, the Material Management and Minimization (M^3) Office of Conversion was not able to allocate money for the reactor operators to discuss conversion plans because of ongoing legal actions between GE and the Department of Energy (DOE).[4] In this case, the obstacle to conversion is legal.

NONTECHNICAL OBSTACLES TO REACTOR CONVERSION IN RUSSIA

The committee gathered information on existing Russian civilian research reactors and Russia's conversion program through its meetings in Moscow with State Atomic Energy Corporation (known as "Rosatom") and Russian Academy of Sciences (RAS) scientists and during its site visit and meeting at Joint Stock Company "State Scientific Center—Research Institute of Atomic Reactors" (JSC "SSC RIAR," hereafter abbreviated as "RIAR"), Dimitrovgrad. The committee learned about Russian scientific priorities and how they affect its domestic research reactor conversion decisions.

The conversion of Russian research reactors is of particular importance to the nonproliferation goal of eliminating the use of HEU in civilian applications because greater than 40 percent of the civilian research reactors using HEU fuel are located within Russia (see Table 2.2 and Figure 2.3a). Russian actions and priorities for conversion of its domestic research reactors have

[3] The TREAT reactor is currently shut down but will restart operations using HEU fuel. Plans for conversion include the development of an entirely new type of LEU fuel. See Appendix E for a short description.

[4] See http://pbadupws.nrc.gov/docs/ML1410/ML14107A187.pdf.

differed dramatically from those pertaining to conversion of nondomestic, Russian-designed, civilian, research reactors.

Russia early recognized and acted on the risk associated with civilian HEU use.[5] In the 1980s, the Soviet Union began a two-stage program to reduce fuel enrichment in Russian-designed research reactors outside its borders, first to 36 percent and then to less than 20 percent (Arkhangelsky, 2011). In the 1990s, Russia and the United States, in the context of the Reduced Enrichment for Research and Test Reactors (RERTR) Program (Diakov, 2014), collaborated on the development of LEU fuel for Russian-supplied research reactors abroad. In 1994, Russia initiated the program "Creation of fuel rods and fuel assemblies with 20 percent uranium-235 (^{235}U) enrichment fuel for the cores of research reactors" (Aden et al., 2006). In parallel, Russia, the United States, and the International Atomic Energy Agency (IAEA) developed a tripartite agreement on HEU fuel removal and repatriation to establish the Russian Research Reactor Fuel Return (RRRFR) Program.[6] Under this program, all Soviet-supplied reactors outside the borders of the Soviet Union were converted, and nearly all fresh and spent HEU fuel has been returned to the Russian Federation. There has also been continuing progress in the conversion of research reactors in countries that were part of the former Soviet Union, with research reactors in only Belarus and Kazakhstan awaiting conversion (see Table 2.2 and Appendix E; Diakov, 2014).

Topics in the nuclear arena that have high priority in Russia include developing the fast reactor technology and addressing the nation's nuclear waste legacy (see Box 5.1). Conversion to LEU is not a priority. Although conversion progress has been halting, there has been notable progress in recent years. The technical arguments against conversion for most of the Russian research reactors to LEU fuel have dissipated since 2010, as discussed below, but there remains little political support to convert domestic Russian research reactors. The preferred approach is to retain fissile material at the reactors and to physically protect it (Khlopkov, 2015).

There are many HEU-fueled, civilian, research reactors in Russia, although the list of operating civilian reactors has decreased to 32, almost entirely through the shutdown of facilities (see Tables 2.2 and 6.1; Arkhangelsky, 2015). About one-half of the remaining operating civilian research reactors are zero-power reactors (critical and subcritical assemblies). These reactors pose a particular risk (see Chapter 2), because the

[5] Setting aside the risk of theft by a non-state actor, conversion is more effective at reducing nuclear threats in a non-nuclear-weapon state than in a nuclear-weapon state so that the non-nuclear-weapon state does not have ready access to weapon-usable material.

[6] Other fuel return programs managed by DOE include the U.S.-origin fuel return and gap materials return programs. These are discussed in Chapter 6.

BOX 5.1
The Changing Landscape of Russian Science

Several recent decisions and events are changing the face of Russian science and technology and are affecting U.S.-Russian collaborations. Rosatom has control over a larger proportion of funding for reactor-relevant science following the reform of the Russian Academy of Sciences.[a]

Rosatom has deemphasized its basic research program and is now heavily focused on funding commercially viable science projects. Rosatom is highly motivated to seek commercial markets for its products, including fuel and radioisotopes. The redirection of Russian funding away from basic research toward projects with potential for commercial success, particularly for export, is dramatic. This redirection has moved reactor conversions down the priority list even farther than they already were. That said, if there is a non-Russian market for products coming from research reactors (e.g., radioisotopes), consumer requirements for products produced using only LEU fuel could be a means of incentivizing continued Russian progress in reactor conversions. Alternatively, there is potential to focus efforts to shut down research reactors that are underutilized, for example, critical assemblies.

[a]See http://www.nature.com/news/academy-reform-is-stifling-russian-science-1.15486.

fuel is often lightly irradiated, hardly consumed, and may be part of a large inventory (hundreds to thousands of kilograms). The number of critical assemblies has decreased in recent years, and it is likely that more will shut down in coming years because of more powerful computer codes, which make some of these reactors unnecessary. In addition, significantly less civilian HEU is used in Russia compared to 10 years ago (Khlopkov, 2015). No civilian facilities are currently under construction or in the planning stages in Russia that will use HEU fuel.

Early in the nonproliferation effort, the Soviet Union rejected the idea of converting its domestic research reactors because civilian HEU use was not seen as a proliferation risk in light of the fact that the former Soviet Union was a nuclear weapon state. Beginning in 2012, a U.S.-Russia collaboration supported a study on the feasibility of converting six Russian research reactors to LEU fuel.[7] The study led to the conversion of one reactor (Argus reactor at the Kurchatov Institute) and the conclusion that it was feasible to convert some of the remaining five research reactors. These studies support a more general conclusion that most of the other Russian research reactors could be converted to LEU without loss of performance,

[7] See http://nnsa.energy.gov/mediaroom/pressreleases/jointstatement062612.

given sufficient political priority and funding for conversion and new LEU fuel (which is expected to be more expensive than existing fuel, as discussed in Chapter 4). As a result of these U.S.-Russian feasibility studies and the Russian Academy of Sciences (RAS)/National Academy of Sciences (NAS) workshop (NRC, 2012), the technical feasibility and challenges of conversion are better understood by both countries than they were 5 years ago.

Although most of the Russian HEU-fueled HPRRs can be converted to LEU using current or likely soon-to-be-available fuel, six reactors and critical assemblies, SM-3, SM-3 CA, RBT-6, RBT-10/2, PIK, and PIK-FM, cannot. The conversion decisions for the two RBT reactors and SM-3 at RIAR are coupled. The RBT reactors are important to Rosatom's plan to significantly increase molybdemum-99 (^{99}Mo) production for sale, mostly outside of Russia. It is technically feasible for the RBT reactors to operate with LEU fuel. However, the RBT reactors use partially burned HEU fuel from the SM-3 reactor as their fuel source.[8] Because Russia has no plans to change the current fuel utilization scheme between the two reactors and the SM-3 reactor cannot convert to LEU fuel without impacting its performance, the RBT reactors will not convert either.

The conversion of Russia's domestic civilian research reactors is largely a matter of priorities and economic challenges, coupled with resistance on the part of reactor operators and users (a problem not confined to Russia). The confidence of Russian authorities in the effectiveness of physical security measures to secure HEU fuel at civilian sites serves to further decrease the level of priority given to reactor conversions.

Russia is pursuing the development of new LEU dispersion fuel based on a UMo-Al matrix clad in Al using traditional extrusion technology as discussed in Chapter 4 (Izhutov et al., 2013). This fuel is primarily aimed at the international market, however, and there are no near-term plans to use the fuel to convert Russian domestic civilian research reactors. Countries that are potentially interested in purchasing the fuel include the Netherlands, Poland, and Kazakhstan.

Finding 10: Nearly all civilian research reactors located outside of Russia that use Russian fuel have been converted to low enriched uranium (LEU), with most of the Russian-origin highly enriched uranium (HEU) returned to Russia. A high fraction of the remaining civilian research reactors worldwide that use HEU are within Russia. Converting most of these to LEU is possible with existing or soon-to-be-qualified LEU fuel. However, conversion of its domestic research reactors is not a high national priority for Russia.

[8] This utilization of partially burned fuel results in a higher level of burnup and fuel utilization than would be achieved by using the fuel in SM-3 only.

Finding 11: Russia is financially motivated to provide low enriched uranium (LEU) fuel to other countries that are interested in using higher-density LEU fuels to improve reactor performance.

Nontechnical obstacles to reactor conversion in Russia have been compounded by the deterioration of U.S.-Russian relations in recent years. One consequence is that Rosatom and the U.S. DOE have severed nearly all ties. Rosatom is no longer willing to accept U.S. funds to pay for activities that are not aligned with Russia's highest nuclear priorities. DOE and the U.S. Congress have ceased funding for the Russian conversion programs that have made significant progress in recent years. Therefore, it is currently not possible for the United States to fund reactor conversions in Russia, which might have overcome Russian political inertia on the matter. Russia effectively ended cooperative threat reduction efforts in 2014. At nearly the same time, DOE suspended interactions between scientists at the DOE National Laboratories with Russian counterparts.

Finding 12: The Russian-U.S. collaboration on research reactor conversion that had been stable for several decades has all but ceased during the past year. Russia is no longer willing to accept funding from the United States for conversions of its domestic civilian research reactors (a previous approach that led to feasibility studies and the only conversion of a domestic Russian research reactor). The Department of Energy has ceased funding Russian conversion programs and curtailed interactions between scientists at its National Laboratories and Russian counterparts. One particularly valuable aspect of the collaboration was development of long-term relationships between U.S. and Russian scientists.

Finding 13: Given current international relations in general, and the current state of U.S.-Russian relations in particular, the United States and the international community have little influence on Russian prioritization of its domestic research reactor conversions.

The fruitful U.S.-Russian collaborations that have been established in past years are currently on hold. Given the importance of personal relationships and maintaining and building on the levels of trust that have been established between scientists, it is important to find ways to continue dialogue and interactions to the maximum extent possible. Ideas for such interactions include the following:

- Utilizing the memorandum of understanding[9] between the Academies and RAS, which allows for discussions among U.S. and Russian scientists. RAS President Fortov reported that at a recent meeting President Putin emphasized the importance of maintaining scientific relationships and avoiding damage to existing relationships.[10]
- Recognizing the differences of each country's scientific priorities so that joint collaborations can be developed that mutually address these priorities.
- Continuing interaction and dialogue in international venues such as Reduced Enrichment for Research and Test Reactors (RERTR) annual meetings and the IAEA meetings and activities.

Recommendation 5: The United States should encourage and facilitate periodic workshops and meetings that especially engage U.S. and Russian scientists and engineers to continue scientific exchanges and interactions that formed the basis for previous progress in highly enriched uranium (HEU) minimization. These interactions should also seek areas of mutual interest that would result in HEU minimization, jointly study the risks and benefits of low enriched uranium conversion, and identify possible collaborations.

NONTECHNICAL CHALLENGES IN OTHER COUNTRIES

Nontechnical obstacles affecting conversion or shutdown decisions are present in countries other than the United States and Russia. The U.S. conversion program has attempted to address technical and nontechnical obstacles to conversion through a variety of means. In many cases, engagement with international bodies or multiple countries is a key to successful navigation of the path to HEU minimization. For example, the Nuclear Security Summits provide incentives to individual research reactor sites to encourage conversion, such as paying for fuel loads or facility upgrades.

Nontechnical Challenges Associated with New Fuel Development Efforts

Significant and technically credible efforts to develop high-density LEU fuels are under way at several sites in Europe, as discussed in Chapter 4. The U.S. program cooperates with and provides about $4 million/year in funding (a portion of which goes to U.S. researchers supporting the Euro-

[9] See http://sites.nationalacademies.org/International/international_052202.

[10] Information gathered during committee discussions held during July 15, 2015, meeting with Russian Aademy of Sciences' President Vladimir Fortov.

pean effort).[11] This research and development effort is complementary to the U.S high-density fuel development effort. This committee recommended in Chapter 4 (Recommendation 3) that the progress of the European high-density fuel development be closely monitored by the United States and the fuel being developed by the Europeans (and South Koreans) be considered as a backup option to the high-density fuel being developed in the United States.

Although there is clearly an exchange of information between scientists and engineers engaged in both development efforts, through international meetings as well as periodic exchanges between programs, the committee judges that there is room for improvement in the interactions. Specific opportunities include increasing the level of detail in the information exchanged and more actively pursuing common areas of interest through increased cooperation and even collaboration. Increasing the quality of communications, cooperation, and cross-fertilization of scientific discoveries and approaches could accelerate fuel development in both programs and also allow better-informed fuel development and qualification choices.

ENCOURAGING EXAMPLES OF OVERCOMING INTERNATIONAL CHALLENGES IN REACTOR CONVERSIONS

Although the nontechnical obstacles confronting civilian research reactor conversions may seem daunting, there has been significant success in dealing with them, particularly through the engagement of international agencies and multiple countries. Examples of research reactor conversions that were technically "straightforward" but impeded by a variety of nontechnical obstacles are illustrated in this concluding section. These reactor conversions were technically straightforward insofar as LEU fuel was readily available to convert the reactor with little impact to its mission. However, these conversions have frequently required a great deal of diplomatic work, international cooperation, political tact, ingenuity, and common sense. The key to success in these projects is that all international partners worked together to address specific challenges unique to each conversion effort.

Development of a Domestic Source of LEU

The government of Chile was willing to convert its research reactor to LEU fuel, but only if the silicide replacement fuel was fabricated in-country. International cooperation was required to establish a Chilean fabrication

[11] Chris Landers, written communication, August 4, 2015: information on the GTRI and M^3 conversion programs' budget details over the past 5 years. See also Box 4.2.

facility, including construction, personnel training, and fuel qualification. Conversion to LEU was successfully accomplished in 10 years (Thijssen et al., 2006).

Desire for an International, Rather than Bilateral, Framework

The Mexican government wished to convert its research reactor to LEU and arrange for spent fuel take-back under an international framework rather than under a bilateral country-to-country agreement. In this case, the IAEA facilitated the necessary policy agreements, carried out fuel inspections in France and Mexico, and served as the intermediary for fuel transfer between the United States and Mexico (Adelfang et al., 2012).

Conversions Involving Multiple Countries with No Previous Engagement in HEU Minimization Efforts

China, which had no prior involvement in U.S. or international HEU minimization or reactor conversion activities, built and installed several small HEU-fueled reactors in China (two operating), Ghana, Iran, Nigeria, Pakistan, and Syria. None of these countries had any prior commitment to HEU minimization objectives.[12] The Chinese-built Miniature Neutron Source Reactors (MNSRs) are low power (approximately 30 kW) with cores of approximately 1 kg of HEU (greater than 90 percent enriched). The MNSRs are used for education, training, and neutron activation analysis among other applications.

The U.S. Global Threat Reduction Initiative (GTRI) Convert Program established a project through the IAEA in 2005 to determine the feasibility of converting these MNSRs to LEU fuel. All countries operating MNSRs participated in the project. An IAEA feasibility study concluded that the MNSRs were convertible with LEU fuel of about 12.5 percent enrichment. A generic safety analysis report that could be used in reactor-specific safety analysis reports was also developed under the IAEA project. The China Institute of Atomic Energy (CIAE) was involved in the fabrication and preparation of the LEU cores for conversion of these reactors. As a result, a Zero Power Test Facility (ZPTF) was built at CIAE in cooperation with GTRI. The ZPTF performs the measurements for each specific LEU reactor core and makes adjustments before shipping the core to the reactors for installation (Roglans-Ribas and Landers, 2011).

An MNSR Conversion Working Group, coordinated by the IAEA, was created in 2011. Its main objective is to coordinate activities and decision-making processes related to the conversion of MNSRs to LEU and shipping

[12] See https://www.iaea.org/OurWork/ST/NE/NEFW/Technical-Areas/RRS/mnsr.html.

of the HEU fuel to China. The first of the conversions is now under way (Adelfang et al., 2008; Jonah, 2014; Odoi et al., 2014).

International Engagement to Address a Technical Concern

Sometimes international engagement is also helpful in addressing technical concerns associated with reactor conversion. For example, the Libyan government decided to convert its research reactor to LEU fuel, but it had safety concerns because the new LEU fuel had not been previously used to operate a research reactor. Addressing these concerns required engagement of an international fuel expert who worked with a Libyan counterpart to assess the quality control at the Russian facility responsible for fabricating the LEU fuel. At the reactor site, an international team helped install an underwater inspection system, a sipping test facility,[13] and a custom endoscope to visually inspect the fuel surface in the Libyan reactor and then trained local staff to operate these tools (Bradley et al., 2006).

Keys to Success

The vignettes above illustrate that each country has its own set of concerns about converting a research reactor to LEU fuel. In many cases, these issues stem from political sensitivities, such as a desire for a country to have control over its fuel supply chain, the prestige of having an HEU-fueled research reactor, or concerns about how its international interactions are seen by others. In addition, countries that have not previously been involved in HEU minimization do not automatically see the benefit of reactor conversion. Each conversion is unique and unpredictable, so being flexible in approaching conversion and having a "toolbox" of incentives and options based on past experiences may help guide future conversions. The common thread in these examples is the engagement of international agencies, especially the IAEA, as well as the constructive involvement of other countries.

[13] A sipping test facility samples the cooling water locally along an irradiated fuel element, measuring for contamination to establish the fuel element's integrity without having to wait for cooling and post-irradiation examination (PIE).

6

Conversion Program: Status and Management

This chapter contains the committee's review of the current status and progress toward conversion of existing research reactors using highly enriched uranium (HEU) fuel and the U.S. Department of Energy's (DOE's) progress and approach to managing the conversion program. These reviews were called for in Tasks 2 and 3 of the study charge.

REVIEW OF CIVILIAN RESEARCH REACTOR STATUS

As noted in Chapter 1, the committee's interpretation of Task 2 was to review progress since the last National Academies of Sciences, Engineering, and Medicine (the Academies) report on medical isotope target and research reactor fuel conversion to low enriched uranium (LEU) (NRC, 2009). Also noted in Chapter 1 was the decision by the committee to include HEU fuel stored at reactor sites (fresh and spent fuel) as part of its charge.

The Convert Program

DOE's Global Threat Reduction Initiative (GTRI) was organized into three pillars: convert, remove, and secure. In 2009, the main activities of the Convert Program were the conversion of mainly nondomestic research reactors and the development of new high-density LEU fuels to enable the conversion of most of the remaining U.S. reactors (see Chapter 4). The scope of and time lines for the Convert Program were as follows (NRC, 2009):

- To convert the remaining 125 research reactors using HEU fuel by 2018.
- To qualify high-density uranium-molybdenum (UMo) dispersion fuel by 2010 and the UMo monolithic fuel by 2011.

DOE's Office of Material Management and Minimization (M^3), established in January 2015, is organized similarly into three main pillars: convert, remove, and dispose ("dispose" replacing "secure" in the program structure).[1] The current activities of the Office of Conversion (previously the Convert Program under GTRI) remain the conversion of nondomestic research reactors and development of very high-density LEU fuel to convert U.S.-based high performance research reactors (USHPRRs). The updated scope and time lines of the Convert Program are as follows:

- To convert or verify the shutdown of the remaining 112 research reactors using HEU fuel by 2035.[2]
- To qualify very high-density UMo monolithic fuel by 2022.

The expanded scope and time lines are discussed in Chapters 2 and 4, and the program decision to focus on UMo monolithic fuel (the "one-for-all" approach) is discussed in Chapter 4. In summary, the scope of the program increased partially in response to the 2009 Academies report recommendation that DOE National Nuclear Security Administration (NNSA) consider defense-oriented research reactors to be within scope (NRC, 2009, p. 162). From 2009 to 2014, the number of reactors on GTRI's conversion list increased from 129 to 200. The time line for completion of the conversion or shutdown of all these reactors increased from 2018 to 2035 (see Figure 2.2). Part of this schedule expansion could be attributed to the larger number of reactors on the list, but unanticipated irradiation test failures of the UMo monolithic fuel and challenges in fuel fabrication and manufacturing also contributed.

Evaluating progress in the U.S. conversion program since 2009 requires consideration of GTRI's accomplishments since the start of the conversion program in 1978. Figure 6.1 shows the number of research reactor conversions and shutdowns since 1978 (the start of the Reduced Enrichment for Research and Test Reactors [RERTR] Program), with projections extending to 2035 (Waud, 2015). The figure shows an increased rate of conversion

[1] The reorganization of the DOE's National Nuclear Security Administration's Office of Defense Nuclear Nonproliferation resulted in the broader material management and minimization activities such as the disposal of mixed oxide (MOX) fuel being grouped with convert and remove.

[2] The Fiscal Year (FY) 2015 budget justification reports that 88 of the 200 identified HEU-fueled research reactors had been converted or shut down (DOE, 2014, p. 462).

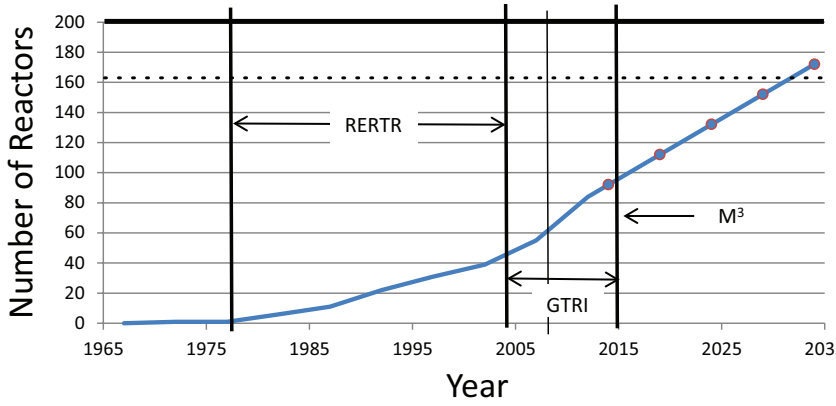

FIGURE 6.1 Number of reactors verified as converted or shut down as a function of time (blue line). The eras of the RERTR Program (1978–2004) and the GTRI Convert Program (2004–-2015) are shown by the vertical lines. The M^3 Office of Conversion was created in 2015. Future conversions and shutdowns are extrapolated to 2035, the projected end date for the conversion program. The horizontal dotted line at 162 research reactors corresponds to the sum of the converted and shutdown reactors (90) and the total number of civilian research reactors currently using HEU fuel as established at the joint International Atomic Energy Agency–Academies meeting (72, see Appendix E). The horizontal line at 200 research reactors is the last reported total research reactors within scope in the NNSA FY 2015 budget request. The vertical dotted line at 2009 indicates the beginning of the period reviewed in the present report. SOURCE: Modified from Waud (2015), Courtesy of the National Nuclear Security Administration (DOE).

beginning in 2004 with the start of GTRI. Part of this increase is a reporting artifact: the RERTR Program did not report shutdown reactors in its totals, but GTRI's Convert Program did. The pace of conversions and shutdowns has remained roughly constant over the past 5 years and is projected to continue at about the same pace through 2035. Although the goal of the program to minimize the use of HEU in civilian research reactors is served both by conversions to LEU fuel and by reactor shutdowns, very few of these shutdowns resulted from an HEU minimization program. Rather, they occurred for other reasons such as reactor obsolescence (e.g., through the development of powerful computational codes), lack of current mission, or cost savings.

GTRI converted (or confirmed shutdown of) a total of 24 research reactors in its first 5 years (2004–2008) (Figure 6.1; further details in Figure 6.2). In 2009, the individual rates of converted and shutdown research reactors changed. Prior to 2009, the program converted 3.6 research reac-

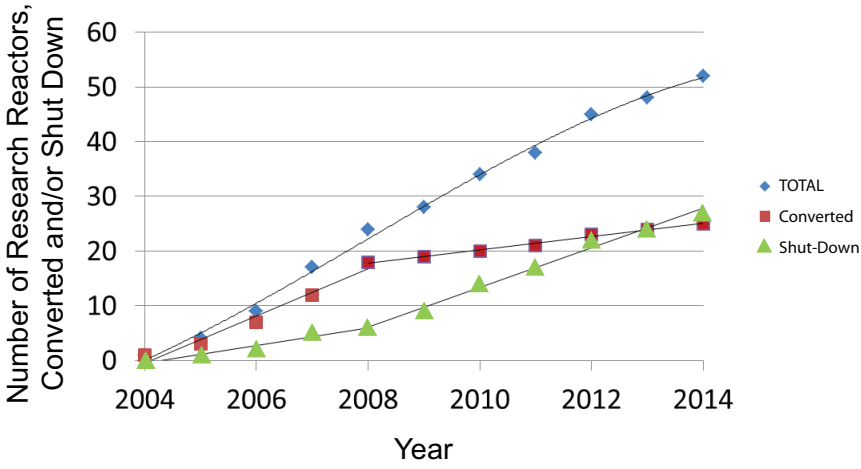

FIGURE 6.2 Reactors converted or verified as shut down by the GTRI Convert Program between 2004 and 2014. The blue diamonds are the cumulative conversions and shutdowns; the red squares indicate conversions only; and the green triangles indicate shutdowns only. The change in slope of the conversion and shutdown lines in 2008 indicates a slowing of conversions and an increased rate of shutdowns. The rate of cumulative shutdowns and conversions is nearly constant. See text and Table 6.1 for more details. SOURCE: Data from Landers, written communication, April 2015.

tors per year and confirmed the shutdown of 1.2 per year on average. After 2009, the program converted fewer research reactors per year (1.5), but confirmed more shutdowns (3.2 per year), as reflected in the changing slopes of the lower lines in Figure 6.2.

Table 6.1 summarizes conversion and shutdown information from 2004 through 2014. The table shows that, since 2009, the number of conversions worldwide has decreased over the previous 5 years, from 18 to 9 conversions. The number of shutdowns has increased from 6 to 19 over the same time period. Notably, nearly one-half of all shutdowns since 2009 have occurred in Russia. Table 6.2 lists all of the reactors that have been shut down or converted since 2009.

By 2009, many of the reactors that could convert with existing fuels had done so. The change in slopes in Figure 6.2 therefore corresponds to a shift in focus to reactors that need new LEU fuel to be qualified to convert (see Chapter 4) and to reactors whose conversions are dominated by nontechnical factors (see Chapter 5). Since 2009, significant work has taken place on developing and testing very high-density LEU fuels (see Chapter 4) and returning a significant amount of U.S.- and Russian-origin HEU fuel to

TABLE 6.1 GTRI Conversion and Shutdown Statistics (2004–2014)

YEAR	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2004-2008	2009-2014
TOTAL worldwide													
Converted	1	2	4	5	6	3	1	1	2	1	1	18	9
Shut down	0	1	1	2	2	1	5	2	4	2	3	6	17
Russia													
Converted	0	0	0	0	0	0	0	0	0	0	1	0	1
Shut down	0	0	0	0	0	0	3	1	1	0	2	0	7
Elsewhere													
Converted	1	2	4	5	6	3	1	1	2	1	0	18	8
Shut down	0	1	1	2	2	1	2	1	3	2	1	6	10
TOTAL worldwide													
Percentage converted	100	67	80	71	75	75	17	33	50	33	25	75	35
Percentage shutdown	0	33	20	29	25	25	83	67	50	67	75	25	65

SOURCE: Modified from data from Landers, written communication, April 2015.

TABLE 6.2 Reactors Converted or Shut Down since 2009

Country	Facility	Site	Converted or Shut Down	Comments and Conversion Status
Bulgaria	IRT-2000	Institute for Nuclear Research and Nuclear Energy	2009	Shut down
United States	RTR—University of Wisconsin - Research Reactor	University of Wisconsin	2009	Full
Hungary	BRR	Atomic Energy Research Institute	2009	Full
United States	NRAD—Neutron Radiography Reactor	Idaho National Laboratory	2009	Full
Russia	PhS-4 (FS-4)	ENTEK	2010	Shut down
Russia	PhS-5 (FS-5)	ENTEK	2010	Shut down
Russia	STRELA	IPPE	2010	Shut down
Japan	KUR	Kyoto University	2010	Full
Chile	RECH-2 Research Reactor	Lo Aguirre Nuclear Centre	2010	Shut down
China	MNSR-SD	Shandong Geology Bureau	2010	Shut down

continued

TABLE 6.2 Continued

Country	Facility	Site	Converted or Shut Down	Comments and Conversion Status
Czech Republic	REZ 10-MW Research Reactor	Nuclear Research Institute, Rez	2011	Full
Russia	BR-10	IPPE	2011	Shut down
Canada	SLOWPOKE Halifax	Dalhousie University	2011	Shut down
Japan	YAYOI	University of Tokyo	2012	Shut down
Japan	MITI Standard Pile	National Metrology Institute of Japan	2012	Shut down
Netherlands	LFR	Nuclear Research & Consultancy Group	2012	Shut down
Poland	MARIA Research Reactor	Institute of Atomic Energy in Otwock-Swierk	2012	Full
Kazakhstan	VVR-K CA	Institute of Nuclear Physics	2012	Full
Russia	RF-GS	IPPE	2012	Shut down
India	Apsara	Bhabha Atomic Energy Centre	2013	Shut down
China	MJTR	Nuclear Power Institute of China	2013	Full
United Kingdom	Consort	Imperial College	2013	Shut down
Russia	ARGUS	Kurchatov Institute	2014	Full
Russia	ROSSIYA	Icebreaker 1	2014	Shut down
Russia	ROSSIYA	Icebreaker 2	2014	Shut down
Uzbekistan	Foton	Foton	2014	Shut down

SOURCE: Modified from data from Landers, written communication, April 2015.

its country of origin.[3] Before the recent deterioration in the U.S.-Russian relationship described in Chapter 5, U.S. and Russian scientists collaborated to study the feasibility of converting Russian research reactors to

[3] See President Obama's Four-Year Initiative (http://nnsa.energy.gov/sites/default/files/nnsa/12-13-inlinefiles/2013-12-12%204%20Year%20Effort.pdf, p. 5). The Fuel Return Program returned 37.3 kg of HEU from Kazakhstan to Russia in December 2014, despite worsening relations between the United States and Russia (communication with Sarah Dickerson, NNSA, January 2015).

LEU, completed the conversion of one Russian domestic research reactor, and established that most other Russian domestic research reactors could be converted.[4] The United States and Russia also continued to work together to return HEU fuel to its country of origin.

The Remove Program

The fuel Take Back Program, the "remove" pillar of GTRI, was originally established to provide a path for the removal of U.S.-origin HEU fuel and spent LEU fuel as an incentive to countries to convert. Like the Convert Program, the Remove Program has expanded its scope over the years; it now includes some weapon-usable material supplied by countries other than the United States as well as additional forms of nuclear material.[5] The Remove Program is organized into three components (Dickerson, 2014):

- **U.S.-origin fuel return program:** The return of U.S.-origin HEU and LEU to the United States for disposition was instituted to encourage countries to convert research reactors from HEU to LEU fuel. By the end of 2014, 1,264 kg of HEU had been removed, with an additional 447 kg slated for removal by 2019. Nearly all of the material under this program has been returned or is planned to be returned by 2019, with the exception of fuel from Canada. The U.S.-origin fuel return program focuses on fuel returning from Training, Research, Isotopes, General Atomics (TRIGA) reactors and materials test reactors (MTR). All of these research reactors have converted and returned U.S.-origin fuel to the United States (or plan to convert by the program's end date).
- **Russian-origin fuel return program:** This portion of the program is dedicated to the return of Russian-origin HEU to Russia for disposition. So far, 2,121 kg of HEU have been removed, with an additional 404 kg targeted for removal by 2020.
- **Gap material program:** This effort addresses weapon-usable materials not covered under the U.S.- or Russian-origin programs. So far, 1,825 kg of HEU and plutonium have been removed, with a goal of removing an additional 1,431 kg by 2022.

[4] The licensing and conversion of four additional Russian reactors had been planned in conjunction with Argonne National Laboratory and Russian laboratories, but the decision to convert has not yet been made and the programs have been put on hold (Roglans, 2015).

[5] However, the Remove Program does not target all U.S.-origin HEU and weapon-usable material. HEU material not associated with research reactor conversion is beyond the scope of the GTRI Convert Program.

Since it began in 1996, the fuel return programs have removed some 5,000 kg of material, including more than 1,500 kg removed in Fiscal Year (FY) 2013 (DOE, 2014; NNSA, 2014), but a significant amount of material—several metric tons—is outside the scope of the return program. The U.S.-origin program is scheduled to end in May 2019 and the Russian-origin program will end in 2022 (a few specific exceptions extend the time line as far into the future as 2029 [Dickerson, 2014]). Legal[6] and logistical issues pertaining to transport of returned material and its final resting place also limit the rate at which material can be returned to the United States.

The M[3] Office of Conversion currently reports progress toward its goal of eliminating HEU from civilian research reactors by counting the number of reactors using HEU that have either converted or shut down. These numbers can be seen in annual reports to Congress (e.g., DOE, 2014) or during presentations at international meetings such as the annual RERTR or European Research Reactor Fuel Management (RRFM) meetings. However, this metric does not fully convey progress toward minimizing and eliminating use of HEU fuel for research reactors for two reasons. First, M[3] defines a "converted" reactor as one in which at least one LEU fuel assembly has been inserted. In the case of some reactors, HEU fuel remains in the reactor until the conversion is complete.[7] In addition, this metric does not measure how much HEU fuel is in place at research reactors, whether it is in-core or in storage (fresh or spent fuel).

The conversion of the University of Michigan (UM) Ford Nuclear Reactor (FNR) in 1981 suggests the need for additional conversion metrics. The FNR conversion was the demonstration project for the RERTR Program. Using the current M[3] conversion metric, the number of existing HEU-fueled civilian research reactors decreased by one in 1981.[8] However, spent HEU fuel remained at UM until October 1987, when it was shipped to the Savannah River Nuclear Solutions. Consequently, the threat posed by this HEU fuel remained largely unchanged for almost 6 years.

A full assessment of the progress of the reactor conversion program is a function of the number of HEU-fueled reactors, the number of research

[6] Federal facility agreements (FFAs, also known as "tri-party agreements") between the U.S. Environmental Protection Agency (EPA), DOE, and states involved in federal cleanup of U.S. government nuclear sites govern the types and amount of spent nuclear fuel allowed within the state. The FFA between EPA, DOE, and South Carolina can be found at http://www.srs.gov/general/programs/soil/ffa/ffa.pdf.

[7] For some reactor cores, fuel replenishment takes place one (or several) fuel element(s) at a time. Fully converting a core to LEU fuel can take years, depending on the refueling schedule of the reactor.

[8] This was RERTR's first domestic conversion originally described as a "physics demonstration." No HEU was shipped to FNR after December 1981. The time from the first insertion of an LEU fuel assembly to full conversion was 3 years.

reactors that still house fresh and spent HEU fuel, and the reduction in HEU usage. As noted previously, the shutdown of research reactors is often not associated with conversion activities. Although it is important to keep track of which reactors using HEU fuel remain operational, counting a shutdown reactor as progress toward conversion totals is not entirely accurate. A shutdown reactor does, however, count toward the M^3 goal of HEU minimization, but only if all HEU is removed from the reactor site. In addition, recall that a small number of civilian research reactors are responsible for the majority of annual HEU consumption (Figures 2.3a,b).

Finding 14: There has been continuing progress in research reactor conversions and shutdowns since 2009. While the pace of reactor conversions has slowed, the pace of shutdowns has increased significantly.

Recommendation 6: The Material Management and Minimization's Office of Conversion should augment its annual progress reports to include the following:

- **a. Identification of the number of conversions in progress (i.e., with at least one low enriched uranium [LEU] assembly inserted into the core);**
- **b. Identification of the number of conversions completed, including the removal of highly enriched uranium (HEU) fresh and spent fuel from the site;**
- **c. Separate reporting of reactors that have fully converted to LEU from those that have been verified as shut down;**
- **d. Reduction of the aggregated inventory of HEU fuel at reactor sites (including shutdown reactors) attributable to the conversion program; and**
- **e. Reduction in the amount of weapon-grade HEU fuel shipped to HEU-fueled research reactors during the reporting period attributable to the conversion program.**

The committee acknowledges the challenges posed by reporting detailed quantities of HEU stores. Therefore, this recommendation provides for flexibility in how amounts of HEU can be aggregated to allow public release.

ASSESSMENT OF DOE'S MANAGEMENT OF REACTOR CONVERSIONS AND HEU MINIMIZATION

The M^3 Office of Conversion confronts several challenges that were not as apparent in the past (e.g., prior to the last Academies report). Managing them will require sustained political and financial support from multiple administrations, technical acumen, and careful management of the program.

The Nuclear Security Summits have been excellent venues for achieving international agreement for HEU elimination and commitments for reactor conversion (Landers, 2014). The last summit will be held in March 2016; it is not clear what, if anything, will take their place. The end of the summits suggests a diminishing of U.S. focus on HEU minimization efforts (Dickerson, 2014).

U.S.-Russia cooperation on reactor conversions has cooled after more than a decade of growing trust and collaboration (Madia, 2015; Roglans, 2015). This is clearly a blow to HEU minimization in light of the large number of remaining HEU-fueled research reactors in Russia and the mismatch in priorities that U.S. and Russian policy makers place on conversion.

There continue to be international dynamics that make engagement on research reactor conversion and HEU removal extremely difficult, if not impossible, in some countries. For example, the Democratic People's Republic of Korea (DPRK) has steadfastly refused to engage with the international community regarding conversion of its civilian research reactors to the point that the experts participating in the joint International Atomic Energy Agency (IAEA)–Academies meeting (Appendix E) were unable to say definitively how many civilian research reactors are in the DPRK or what their condition may be. It is not possible to predict when engagement and conversion will be possible. Bluntly, most of the "easy" conversions have already been completed or are in progress.

In short, the pace of many international research reactor conversions depends on factors that are completely outside of the Office of Conversion's control, for example, Russian cooperation. Timetables for reactor conversions and HEU removal that might have seemed reasonable not long ago now seem optimistic.

Finding 15: The Material Management and Minimization Office of Conversion's current plan for conversion of all the civilian research reactors currently using highly enriched uranium (HEU) fuel by 2035 is highly uncertain, primarily because of nontechnical factors.

The M^3 Office of Conversion's program scope for conversion has nearly doubled since 2005 (see Figure 2.2). This increased scope requires additional funding, staffing, and/or time. The scope of the M^3 Office of Conversion may be revisited based on the list of HEU-fueled civilian research reactors produced during the joint IAEA–Academies meeting. The program scope needs to be clearly defined, and the time lines and resources need to be aligned with that scope.

The M^3 Office of Conversion has underestimated the challenges in developing and qualifying LEU fuels for high performance research reactors (HPRRs). This is the major reason why conversion schedules for HPRRs

have expanded so dramatically. The fundamental understanding of UMo monolithic and dispersion fuels has increased, and fuel developers are confident that upcoming irradiation tests will be passed (Meyer, 2014, 2015; Van den Berghe and Lemoine, 2014); however, it is still not assured that the fuel will be successfully qualified and the reactors converted. The Office of Conversion must better manage its technical risks if it expects to be successful in converting the remaining HPRRs, especially HFIR.

Managing Technical Risk

Two events in the mid-2000s resulted in a "program reset" in 2009 for GTRI's Convert Program: UMo dispersion fuel irradiation failures (see Chapter 4) and technical disconnects between fuel design and manufacturing requirements. Following the irradiation test failures in 2006, efforts were initiated to better understand the material interactions leading to failures, and a new fuel system, UMo monolithic fuel, was explored. At the same time, the U.S. conversion program began to plan for manufacturing of the UMo monolithic fuel. Initial assessments identified potential manufacturing challenges. The program "reset" reassessed fuel development decisions and time lines with input from the fuel manufacturing and the fuel development technical leads. Time lines for fuel development and manufacturing were expanded after program managers recognized the extent of the technical challenges involved.

The largest technical obstacle to HPRR conversion is the qualification and fabrication of the very high-density UMo monolithic fuel (Rabin, 2015), especially for HFIR. The selection of fuel for converting USHPRRs evolved over time in response to failures of other fuel types. The first efforts at fuel development began with modifying existing dispersion fuels (the silicides), essentially by increasing their uranium density. When it was determined that the silicide fuels would not offer the densities needed by the HPRRs, the effort shifted to identifying fuel that was different in composition but structurally similar so that it could be manufactured in a similar manner to existing fuels. This effort resulted in the selection of high-density UMo dispersion alloys. However, this fuel proved incapable of providing the required uranium density for the USHPRRs. This drove fuel developers to another new fuel material with different fabrication and manufacturing requirements (i.e., very high-density UMo monolithic fuel fabricated by co-rolling; Robinson et al., 2013). By the time the UMo monolithic fuel was identified, the fuel development effort was significantly behind the original schedule. That left no time for exploration of alternative fuel formulations that have more suitable manufacturing characteristics. The current fuel development and fabrication programs are moving forward under tight deadlines with limited options to explore

alternative material or fabrication processes and little room for error (Burkes, 2015).

The full life cycle of the fuel, including manufacturing, processing of scrap, and disposition of spent fuel, was not seriously considered as the fuel formulation was finalized. The steady evolution of the fuel away from well-known materials and processes has resulted in a number of technical "surprises" that have required significant engineering advances to overcome (Van den Berghe at al., 2015; Meyer, 2015). The additional time to address these surprises has lengthened the time lines for converting the USHPRRs even further (see Chapter 2). The current program roadmap shows a critical pathway to completing conversion of the USHPRRs by 2032 (see Figure 4.9).

Addressing the remaining technical risks for the conversion program requires taking a broad, critical look at the entire fuel development, fabrication, and manufacturing process, up to and including reactor conversion and back-end processes for spent fuel and scrap material. The M^3 Office of Conversion has instituted reviews of some aspects of fuel development and conversion to mitigate this risk. Individual teams are performing independent strategic, cost, and fuel development reviews.

A group of independent experts is performing the independent strategic review (ISR). The ISR has met twice since its formation in April 2013 and has reviewed the overall management of the conversion program and its pillars: fuel development, fuel fabrication, and conversion. The ISR group was not charged with evaluating the technical details of the conversion program; rather, it relies on the fuel development review team to provide technical review to guide its advice.

The ISR group supports the current approach for managing the program, noting that the program managers are flexible and open to change. However, the ISR group also identified the lack of a systems-level review and a slow response to technical issues (the ISR group noted that technical issues were often being overwhelmed by political and geopolitical challenges). The ISR group identified the long time line for conversion as the highest-risk item for the program because continued funding and administration support while stable for many years is not guaranteed (Madia, 2015; Marra, 2015).

The committee agreed with many of the ISR group's conclusions. For example, the committee sees no immediate need for concern that support has waned but also acknowledges that the nature of the U.S. political system does not guarantee that strong support will continue indefinitely. The committee also found a rigorous, systematic review of the conversion program to be lacking. The lack of a systems approach to the identification and development of high-density UMo fuel has created technical and schedule challenges for the fuel fabrication and manufacturing efforts, as

discussed previously. Going forward, an integration of design, fabrication, and manufacturing efforts across the conversion program would reduce the risks associated with qualifying a new fuel that is acceptable for use in USHPRRs and also manufacturable, affordable, and amenable to back-end processes. There is evidence that the M^3 Office of Conversion has increased its emphasis on this critical aspect of the effort by adding an "integration" pillar and a systems analyst to the program staff. However, work is still required to ensure that this systems-level thinking pervades the program. The committee was unable to assess how the additional integration pillar and the new systems analysis expertise are being applied, because these capabilities were recently added.[9]

The cost review was focused on methods and systems in place for estimating costs, and not specific cost estimates.[10] It did not address estimates of the cost of converting HPRRs or LEU fuel. HPRR operators are extremely concerned about the cost of LEU fuel, but there is no credible estimate of such costs. The rough estimate of relative costs provided by Babcock and Wilcox Technologies (BWXT; see Table 4.2) assumes that the yield for LEU fuel assemblies will be 88 to 90 percent, which is the value achieved in the manufacture of HEU fuel assemblies. Given the dramatically different manufacturing processes that will be required for monolithic UMo fuel, this assumption strikes the committee as overly optimistic. There is a particular need for a rigorous review of LEU manufacturing costs.

The fuel development review is the only *technical* review in the conversion program of which the committee is aware. The members of the review team are reactor fuel experts (Hobbins, 2015). The membership of this group, while technically strong, has a close association with the GTRI/M^3 Office of Conversion and its fuel development efforts. This gives the appearance that the fuel development technical review does not have the level of independence that would be most beneficial to the conversion program. Experts with no direct (past or present) ties to the fuel development program could provide more critical evaluations and generate broader thinking. Box 4.2 highlights similarities and differences between the European and U.S. fuel development and manufacturing programs. Technical reviews within the European program consist of expert groups that include U.S. fuel development experts.

The fuel development review focused only on the fuel development activities of the fuel program. The most recent reviews have focused on measurements of bond strength in monolithic fuel, residual stress in monolithic fuel plates, microstructure of as-fabricated and irradiated fuel, and

[9] A systems-level report on fuel-cycle back-end options was recently produced.

[10] Scott Dam, chair of the cost review for the conversion program, written correspondence, dated March 12, 2015.

fuel specifications. The committee found this review to be valuable but insufficient by itself, because fuel is useful only if it can be fabricated reproducibly, manufactured affordably, used to convert research reactors, and processed as both scrap and spent fuel (Burkes, 2015). The lack of an independent technical review of each phase of the fuel development, fabrication, manufacturing, and utilization life cycle is a serious shortcoming in the management of the conversion program.

It is imperative to have external, independent technical review of both the details of each aspect of the effort separately and of the full spectrum of effort. The significant delays relative to previous timetables in the fuel development and qualification program that are now expected for project completion have arisen largely for technical reasons. Technical risks in such a complex project could be identified through the use of regular, *independent, external technical* peer review by appropriate groups of technical experts.[11] This approach is part of the culture in other parts of DOE (e.g., in the Office of Science, especially for its construction projects) and generally works very well. Combined with execution of formal project management and the effective programmatic evaluation that the project has already successfully implemented through its independent strategic review process, such technical oversight will be essential for successful and timely conversion of USHPRRs.

Execution of a well-developed technical risk mitigation plan could likely have reduced the delays in developing and qualifying high-density UMo monolithic fuel. The M^3 Office of Conversion has developed a risk mitigation plan[12] that describes detailed processes for identifying and mitigating risks as well as roles and responsibilities of project participants. The program has also developed tables of risks that are tracked on a monthly basis according to a documented process. The plan seems reasonable and complete, but it must be executed conscientiously and with a healthy dose of critical, independent, and questioning thinking to be effective in mitigating risks in the conversion program.

Finding 16: There has been a lack of rigorous systems analyses of the U.S. conversion programs as evidenced, for example, by the lack of involvement by the fuel fabricators during fuel development. The lack of risk management within the program likely lengthened the fuel development schedule. The M^3 Office of Conversion's risk management

[11] For example, the HERACLES program has two levels of expert groups that guide management decisions through technical review; technical experts from the U.S. conversion program participate in these reviews. The committee is unaware of technical experts from HERACLES participating in M^3 technical reviews.

[12] The committee was provided with the August 2014 version of this plan.

and systems analysis programs are positive developments but are new and unproven.

As the fuel qualification effort, particularly the development of manufacturing processes, matures, it will be important to establish metrics to gauge progress against program milestones. Such metrics might include the numbers of fuel plates produced, yields, or amounts of scrap material produced (and reclaimed). These metrics could supplement the independent technical review that is currently used to keep the program on track.

Finding 17: The technical setbacks and increasingly longer time lines for the conversion of U.S. high performance research reactors emphasize the need to incorporate regular independent technical and programmatic evaluations into the Office of Conversion program manager's decision-making process.

Finding 18: Review teams have been established by the M^3 conversion program in recent years to guide program management decisions. However, the technical review of fuel development was not performed by a team with the appropriate independence and institutional diversity needed for critical evaluation. Technical review of other parts of the program, such as fuel fabrication, does not currently exist.

Recommendation 7: In depth independent technical review of each aspect of the fuel life cycle (from fuel development, fabrication, recycling, and spent fuel management), as well as integration of the technical components, should be conducted to ensure that the newly instituted risk and systems analysis capabilities within the Material Management and Minimization Office of Conversion develop into robust project and risk management. These reviews should be conducted by qualified, independent, and diverse external experts.

7

Conclusion

Two communities must work together to convert a research reactor, but they often have conflicting goals: researchers and operators of the facilities and those supporting the nonproliferation conversion programs. Two of the recommendations provided, if implemented, could offer a way for these two communities to advance each of their respective goals. Developing a 50-year strategy for neutron research in the United States (Recommendation 1) is connected to the committee-proposed stepwise conversion (Recommendation 4) of the U.S. high performance research reactors (USHPRRs). Negotiation with reactor operators on stepwise conversion—when there is also a clear long-term strategy in place for continued neutron research capabilities in the United States—would allow for wider consideration of conversion options including discussions about shutting down aging reactors or reducing reactor performance while ensuring the continued ability to meet U.S. mission needs with new neutron facilities that utilize low enriched uranium (LEU).

The importance of eliminating highly enriched uranium (HEU) from civilian research reactors is clear. Throughout its work the committee was impressed by the progress made since 1978 in the reduction of HEU in civilian research reactors around the world. More than 90 reactors have been verified as converted or shut down since 1978, with more than 26 of those conversions or shutdowns occurring since 2009. The 90-reactor estimate is incomplete because reactor shutdowns were not counted by the earliest conversion program, the Reduced Enrichment for Research and Test Reactors (RERTR) Program, which led the research reactor conversion effort from

1978 to 2004. This is an accomplishment in which the Department of Energy/National Nuclear Security Administration should take satisfaction.

Seventy-four civilian research reactors continue to use HEU fuel, have HEU on site, or, in the case of one new reactor, have plans to start using HEU in the coming years. Elimination of HEU from these facilities will be significantly more challenging than what has already been accomplished. Success will depend on several developments:

- Qualification of manufacturable, affordable high-density LEU fuels that can be used in high performance research reactors (HPRRs) without significant loss of performance, followed by conversion of these research reactors to LEU fuel.
- Positive engagement with the countries that still have HEU-fueled civilian research reactors, possibly with the additional engagement of international bodies, to incentivize conversion to LEU fuel. Engagement with Russia is particularly important because it operates greater than 40 percent of the remaining HEU-fueled civilian research reactors.
- Demonstration of continued U.S. commitment to the goal of HEU minimization, and ultimately elimination, by taking intermediate steps to limit the use of weapon-usable HEU fuel in U.S.-based reactors en route to full conversion to LEU.

The challenges associated with achieving conversion goals have resulted in dramatically expanded time lines for LEU conversions and HEU elimination relative to what was projected 5 years ago. A number of issues have come to light since the previous Academies report on conversion and medical isotope production (NRC, 2009). In particular, the USHPPRs will be 65 years old on average at the time they are scheduled to be converted; therefore, one can no longer consider LEU conversion without also thinking about plans for a new generation of research reactors. At the same time, no government-wide strategy exists for how the United States will meet its needs for research reactors later in this century. Research reactors are vital components of the U.S. and worldwide science and technology infrastructure. Other countries, especially in Europe, are planning, constructing, and commissioning new reactors to replace aging research reactors and even provide new capabilities, but there is no such activity in the United States. A long-term government-wide strategy for neutron sources, including research reactors, must be developed.

The M^3 Office of Conversion needs stable and effective management and long-term political support to be successful. This holds true even after conversion—fuel costs will likely increase, and it will probably require a

national commitment to maintain reactor operations. To be successful, the Office of Conversion needs to

- Take a systems-level view of the program, including research, fuel qualification and manufacturing, and reactor conversion and back-end processes. This view needs to include rigorous risk management.
- Provide regular, truly independent technical reviews of all technical aspects of the program.
- Explicitly recognize those aspects of the program that are within the control of the M^3 Office of Conversion and those that are not, such as nontechnical obstacles identified in Chapter 5, and develop plans accordingly.

The committee saw indications that the Office of Conversion is recognizing and acting on these needs, which is laudable. The committee hopes that this report will help the M^3 Office of Conversion be successful in its most important mission.

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Appendix A

Statement of Task

An ad hoc committee will conduct a study and prepare a report with findings and recommendations on the current status of and progress toward eliminating highly enriched uranium (HEU) use in fuel for civilian research and test reactors. This study will provide

1. A list of civilian research and test reactors that operate using HEU fuel.
2. A review of civilian research and test reactor status over the past five years, including new HEU-fueled reactors that were planned, under construction, or commissioned; HEU-fueled reactors that were shut down and/or decommissioned; and HEU-fueled reactors that were converted to low enriched uranium (LEU).
3. An assessment of the progress being made by the Department of Energy and others to eliminate worldwide use of HEU in fuel for civilian research and test reactors. This assessment should identify key technical and nontechnical factors responsible for the successful conversion of reactors from HEU to LEU fuel; key obstacles to converting the remaining HEU-fueled reactors; and steps that could be taken to overcome the identified obstacles.

Appendix B

Biographical Sketches of Committee Members

Julia M. Phillips, chair, is the former vice president and chief technology officer at Sandia National Laboratories, a U.S. Department of Energy multiprogram science and engineering laboratory. She was responsible for leading the laboratory's approximately $160 million Laboratory Directed Research and Development Program, research strategy development and implementation, and intellectual property protection and deployment. Dr. Phillips joined Sandia in 1995 after spending 14 years at AT&T Bell Laboratories, where she performed research on epitaxial metallic and insulating films on semiconductors; high-temperature superconducting, ferroelectric and magnetic oxide thin films; and novel transparent conducing materials. Other positions at Sandia included deputy chief technology officer and director of laboratory research strategy and partnerships; director of nuclear weapons science and technology programs; director of the Physical, Chemical, and Nano Sciences Center; and director of the DOE Center for Integrated Nanotechnologies at Sandia and Los Alamos national laboratories. Dr. Phillips is a member of the National Academy of Engineering (NAE) and a fellow of the American Academy of Arts and Sciences, Materials Research Society (MRS), American Association for the Advancement of Science (AAAS), and the American Physical Society (APS). She served on the Council of the NAE and the AAAS Board of Directors and is past chair of the APS Topical Group on Energy Research and Applications and the APS Division of Condensed Matter Physics. She also served as president of the MRS. Her "leadership and pioneering research in materials physics for industrial and national security applications" was recognized by the 2008 George E. Pake Prize. She has served

on the editorial boards of the *Journal of Materials Research*, *Journal of Applied Physics*, and *Applied Physics Reviews*. Dr. Phillips has edited 2 books, written 3 book chapters, and published more than 100 journal papers, 12 major review articles, and 45 refereed conference proceedings publications. She also holds five patents. Dr. Phillips has a Ph.D. in applied physics from Yale University and a B.S. in physics from the College of William and Mary.

Pablo Adelfang recently retired as leader of the Research Reactor Section in the International Atomic Energy Agency (IAEA). Before joining the IAEA in 2003, he worked for 23 years for the Argentine National Commission of Atomic Energy (CNEA), where he served as head of the Department of Nuclear Fuels and deputy director of the Constituyentes Atomic Centre. At CNEA, Lic. Adelfang led the development of high-density fuels for research and test reactors and the installation of the Laboratory for Post-irradiation Examinations. He conducted the successful qualification of low enriched uranium (LEU) silicide-type fuel elements for research and test reactor fuel conversion. He also led the development effort to convert the production of the medical isotope, molybdenum-99 (^{99}Mo), from highly enriched uranium (HEU) to LEU targets. Argentina was the first country to convert its domestic production of ^{99}Mo from HEU to LEU targets. Lic. Adelfang was also responsible for the Argentine participation in the Reduced Enrichment for Research and Test Reactors program and for the Argentine contribution in the international effort to develop very high-density research and test reactor fuel based on uranium-molybdenum alloys. He received his Licenciatura in chemistry from the University of Buenos Aires, Argentina, and later specialized in nuclear chemistry at CNEA.

Gerald Gabrielse is the Leverett Professor of Physics at Harvard University. His previous positions include assistant and associate professor at the University of Washington-Seattle and chair of the Harvard Physics Department. His physics research focuses on making the most accurate measurements of the electron's magnetic moment and its fine-structure constant, and on precise laser spectroscopy of helium. At the European Organization for Nuclear Research (formerly the Conseil Européen pour la Recherche Nucléaire, a.k.a. CERN), Dr. Gabrielse also led the International Antihydrogen Trap, or "ATRAP", Collaboration which pioneered accurate hydrogen spectroscopy and first observed hot antihydrogen atoms. His many awards and prizes include fellow of the American Physical Society (APS), the Davisson-Germer Prize of the APS, the Humboldt Research Award (Germany, 2005), and the Tomassoni Award (Italy, 2008). Harvard University awarded Dr. Gabrielse both its George Ledlie Research Prize and its Levenson Teaching Prize. Hundreds of outside lectures include a

Källén Lecture (Sweden), a Poincaré Lecture (France), a Faraday Lecture (Cambridge, UK), a Schrödinger lecture (Austria), a Zachariasen Lecture (University of Chicago), and a Rosenthal Lecture (Yale University). He is a member of the National Academy of Sciences. He has a B.S. from Calvin College and an M.S. and a Ph.D. in physics from the University of Chicago.

Alexander Glaser is an assistant professor at the Woodrow Wilson School of Public and International Affairs and in the Department of Mechanical and Aerospace Engineering at Princeton University, where he directs the Nuclear Futures Laboratory. His research interests focus on technical aspects of nuclear disarmament and nonproliferation, nuclear transparency and verification, the nuclear fuel cycle, and nuclear energy. Dr. Glaser is the co-editor of *Science & Global Security*. He is the co-chair of the International Panel on Fissile Materials, which publishes the annual *Global Fissile Material Report*. He has consulted for the International Atomic Energy Agency and was a member of a joint working group of the American Physical Society and the American Association for the Advancement of Science on Nuclear Forensics: Role, State of the Art, Program Needs. He has extensively studied and written about the challenges of converting research reactors to low enriched fuel and performed neutronics calculations of Germany's FRM-II reactor, which uses highly enriched uranium fuel. He is a co-author of *Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation*. Dr. Glaser received an M.A. and a Ph.D. in physics from Darmstadt University of Technology, Germany.

David W. Johnson, Jr., is currently an editor-in-chief for the *Journal of the American Ceramic Society*. He is the retired director of materials research at Bell Laboratories, Lucent Technologies, and former adjunct professor of materials science at Stevens Institute of Technology. His research activities included fabrication and processing of glass and ceramics with emphasis on materials for electronic and photonic applications. He is a member of several professional societies, including a fellow, distinguished life member, and past president of the American Ceramic Society. Dr. Johnson won the Taylor Lecture Award and the Distinguished Alumni Award from Pennsylvania State University; the Ross Coffin Purdy Award for the best paper in ceramic literature; the Fulrath Award; the John Jeppson Award; the Orton Lecture Award from the American Ceramic Society; and the International Ceramics Prize for Industrial Research from the World Academy of Ceramics. He is a member of the National Academy of Engineering and the World Academy of Ceramics. He holds 46 U.S. patents and has published numerous papers on materials sciences. He earned a B.S. in ceramic technology and a Ph.D. in ceramic science from Pennsylvania State University.

Patrick Lemoine retired as research director of Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA, the French Atomic Energy Commission) in February 2014 after a 40-year career in structural materials and nuclear fuels for power and research reactors. From 2001 through 2014, Mr. Lemoine directed the CEA program of development and qualification of fuels for research reactors, including the next-generation low enriched uranium fuel (LEU), specifically for the Jules Horowitz Reactor (JHR), the materials testing reactor currently under construction at CEA-Cadarache Center in France. He has worked directly with international fuel developers at laboratories in the United States, Belgium, Russia, Korea, Canada, and Argentina and has participated in numerous fuel development working groups of the International Atomic Energy Agency. He is familiar with European and international research and test reactor fuels. In parallel to his work on JHR fuels, Mr. Lemoine also served as program manager (2001–2009) for safety-related experimental reactors (Cabri and Phébus) and a fast neutron reactor (Phénix). Before that, he served as head of the applied metallurgy unit at CEA-Saclay (1987–1994) and head of the materials unit at CEA-Grenoble (1997–2001). Mr. Lemoine was appointed as an international expert by the CEA in 2009 in the domain of structural materials and nuclear fuels. He received a civil engineering degree from École Nationale des Ponts et Chaussées, where in parallel with his first CEA activities, he taught continuum mechanics for 15 years as lecturer (1972–1987).

William R. Martin is a professor and former chair of the Department of Nuclear Engineering and Radiological Sciences, and former associate dean for academic affairs in the College of Engineering at the University of Michigan. Dr. Martin's primary research area is the development of computational methods for the solution of the Boltzmann transport equation, including neutrons, photons, and electrons. He has graduated 35 Ph.D. students during his career at the University of Michigan. Dr. Martin was the founding director of both the Laboratory for Scientific Computation and the Center for Advanced Computing at the University of Michigan. He has been a member and/or chair of review panels for five different national laboratories: Argonne, Sandia, Lawrence Livermore, Oak Ridge, and Los Alamos. He recently served on the National Research Council's Committee to Review the Quality of the Management and of the Science and Engineering Research at the Department of Energy National Security Laboratories—Phase II. Currently, Dr. Martin is a consultant with Los Alamos National Laboratory on the development of Monte Carlo methods for neutron and photon transport, including nonlinear thermal radiation transport and stochastic media. Dr. Martin is a member of the Board of Directors of the American Nuclear Society and has served in several positions

in the Mathematics and Computation Division, including member of the executive committee, treasurer, numerous program committees, and chair. He received his B.S.E. in engineering physics and his M.S.E. and Ph.D. in nuclear engineering from the University of Michigan. He also received an M.S. in physics from the University of Wisconsin and served in the Naval Reactors Division for the U.S. Navy.

Pavel Podvig (technical consultant) is an independent analyst based in Geneva, where he runs his research project, "Russian Nuclear Forces." He is also a senior research fellow at the UN Institute for Disarmament Research and a researcher with the Program on Science and Global Security at Princeton University. Dr. Podvig started his work on arms control at the Center for Arms Control Studies at the Moscow Institute of Physics and Technology (MIPT), which was the first independent research organization in Russia dedicated to analysis of technical issues of disarmament and nonproliferation. Dr. Podvig led the Center for Arms Control Studies project that produced the book, *Russian Strategic Nuclear Forces* (MIT Press, 2001). In recognition of his work in Russia, the American Physical Society awarded Dr. Podvig the Leo Szilard Lectureship Award of 2008 (with Anatoli Diakov). Dr. Podvig worked with the Program on Science and Global Security at Princeton University, the Security Studies Program at MIT, and the Center for International Security and Cooperation at Stanford University. His current research focuses on the Russian strategic forces and nuclear weapons complex, as well as technical and political aspects of nuclear nonproliferation, disarmament, missile defense, and U.S.-Russian arms control process. Dr. Podvig is a member of the International Panel on Fissile Materials. He has a physics degree from the Moscow Institute of Physics and Technology and a Ph.D. in political science from the Moscow Institute of World Economy and International Relations.

Roger Pynn is a professor of physics at the University of Indiana, Bloomington. His research activities focus on the development of novel experimentation methods in neutron scattering, the construction of a beamline at the University of Indiana's Low Energy Neutron Source, and the application of neutron scattering methods to a variety of problems, mainly in macromolecular systems and layered magnetic materials. Prior to his current appointment, he worked at Los Alamos National Laboratory, first as center leader of the Manuel Lujan Jr. Neutron Scattering Center and later as division director of the Los Alamos Neutron Science Center (LANSCE). Concurrent with his work at LANSCE, he was the program manager for Basic Energy Sciences. Prior to coming to LANL, he performed neutron-scattering experiments and developed instrumentation at the Institut Laue-Langevin in France. In 2009, he received Norway's

Gunnar Randers Research Prize for his pioneering work in neutron-scattering studies and uses in advanced materials science. He is a member of the Norwegian Physical Society and the Materials Research Society. He is a fellow of the American Association for the Advancement of Science, the American Physical Society, and the Neutron Scattering Society of America. He served as president of the Neutron Scattering Society of America from 2005 to 2008. He has served on numerous government committees related to neutron and x-ray sources. Dr. Pynn is an invited lecturer and teacher of a highly rated course on neutron scattering at many neutron scattering schools, including the Niels Bohr Institute, the Argonne National Laboratory/Oak Ridge National Laboratory summer school, and the Manuel Lujan Jr. Neutron Scattering School. Dr. Pynn received his B.A. in natural sciences and an M.A. and Ph.D. in physics from Trinity College, University of Cambridge.

William H. Tobey is a senior fellow at the Belfer Center for Science and International Affairs at Harvard Kennedy School. He was most recently deputy administrator for Defense Nuclear Nonproliferation at the National Nuclear Security Administration. There, he managed the U.S. government's largest program to prevent nuclear proliferation and terrorism by detecting, securing, and disposing of dangerous nuclear material. Mr. Tobey also served on the National Security Council (NSC) staff in three administrations—Reagan, George H. W. Bush, and George W. Bush—working in defense policy, arms control, and counterproliferation positions. As director of counterproliferation strategy at the NSC, he oversaw development and implementation of U.S. policy on nuclear programs in Iran and North Korea, was a delegate to the Six Party Talks with North Korea, managed U.S. efforts to dismantle Libya's weapons of mass destruction programs, and authored the first draft of United Nations Security Council Resolution 1540, which criminalizes nonstate proliferation and obligates all states to establish and maintain effective safeguards, security, and export controls. Mr. Tobey previously participated in a variety of international negotiations, including the Nuclear and Space Talks with the Soviet Union and the U.S.-Russia Space Cooperation agreement. He has served on the National Research Council's Committee on Improving the Assessment of Proliferation Risk of Nuclear Fuel Cycles. He received a B.S. from Northwestern University and an M.P.P. degree from Harvard University.

Paul P. H. Wilson is a professor of nuclear engineering in the University of Wisconsin (UW)-Madison's Department of Engineering Physics and faculty director of the Advanced Computing Initiative. Dr. Wilson's experience combines technical and policy issues, such as analysis methods for determining isotopic inventories in nuclear systems and the implications

for nuclear nonproliferation policy, and the development of next-generation nuclear power systems for future energy policy and needs. He expanded and developed the University of Wisconsin's computing and analysis capabilities to support the conversion of the university's research reactor from highly enriched uranium to low enriched uranium fuel. Dr. Wilson was invited to present this work at the 2011 National Academy of Sciences–Russian Academy of Sciences joint workshop in Moscow on Progress, Challenges, and Opportunities for Converting U.S. and Russian Research Reactors. Dr. Wilson served as a consultant for the Blue Ribbon Commission on America's Nuclear Future, contributing a report on the assessment and comparison of civilian nuclear fuel cycle options. At UW-Madison, Dr. Wilson currently serves on the executive committee of the Wisconsin Energy Institute and the steering committee of the Holtz Center for Science and Technology Studies, and is the past-chair of the Energy Analysis and Policy graduate certificate. He is a member of the American and Canadian Nuclear Societies, the American Society for Engineering Education, and the North American Young Generation in Nuclear. Dr. Wilson received his B.S. in engineering science from the University of Toronto. He received his doktor-ingenieur in mechanical engineering from the Karlsruhe Institute of Technology, Germany, and his Ph.D. in nuclear engineering from the University of Wisconsin.

Appendix C

Presentations and Visits

WASHINGTON, DC, OCTOBER 23–24, 2014

- History, Organization, and Goals of Global Threat Reduction Initiative (GTRI) Conversion Program; Christopher Landers, Sr., Reactor Conversion Program Manager, National Nuclear Security Administration (NNSA)/GTRI; Jeffrey Chamberlin, Director, GTRI Office of European and African Threat Reduction
- GTRI Reactor Conversion Program Scope and Status; Jordi Roglans-Ribas, Director of the Nuclear Engineering Division, Argonne National Laboratory, and GTRI Program Manager
- Regulatory Steps for Conversion of Reactors; Alexander Adams, Chief of Research and Test Reactors Licensing Branch, U.S. Nuclear Regulatory Commission
- Main Challenges Facing Research Reactors; Pablo Adelfang, Research Reactor Section, International Atomic Energy Agency
- Highly Enriched Uranium (HEU) Use in Russia; Pavel Podvig, Program on Science and Global Security, Princeton University; Member, International Panel on Fissile Materials
- Challenges of High Performance Research Reactor Conversions; John Stevens, Manager of Research and Test Reactor Department, Argonne National Laboratory
- Conversion Analyses for the MITR-II Reactor; Thomas Newton, Director of Reactor Operations and Associate Director, Reactor Engineering, Massachusetts Institute of Technology

VIA CONFERENCE CALL, DECEMBER 3, 2014

- GTRI Removal Program Overview; Sarah Dickerson, Acting Associate Assistant Deputy Administrator for Global Threat Reduction
- Acceptance and Disposition of the Department of Energy's (DOE's) Spent Nuclear Fuel; Hitesh Nigam, Senior Environmental Engineer, Office of Nuclear Materials Disposition, DOE's Office of Environmental Management

IDAHO FALLS, IDAHO, AND IDAHO NATIONAL LABORATORY, FEBRUARY 26–27, 2015

- Irradiation Performance of U–Mo Alloy Based "Monolithic" Fuel, Including Past Fuel Decisions, Updates on RERTR-12 and AFIP-6, -6 II, and -7 Results; Mitchell (Mitch) Meyer, Fuel Development National Technical Lead, Idaho National Laboratory (INL)
- Fabrication Process Selection Through the MP-1 Irradiation Test; Irina Glagolenko, Principal Investigator, Fuel Development Irradiation Experiment, INL
- Plan for Research Reactor Fuel Qualification Including Base Fuel Qualification Plan and Requirements; Barry Rabin, Fuel Development National Technical Lead Deputy, INL
- Overview of the Fuel Fabrication Capability and U-Mo Fabrication Process; Douglas Burkes, Fuel Fabrication Capability Pillar Lead, Pacific Northwest National Laboratory (PNNL)
- Research and Development Approach for Fuel Fabrication: Challenges and Concerns; Douglas Burkes, PNNL
- NNSA/NA-23 Fuel Development Program Technical Review Committee; Richard Hobbins, Independent Consultant

COLUMBIA, MISSOURI, APRIL 16–17, 2015

- Material Management and Minimization's (M^3's) International Fuel Development Collaborations Including HERACLES; Abdellatif Yacout, M^3 European Fuel Development Technical Lead, Argonne National Laboratory (ANL)
- NNSA's Russian Reactor Conversion Program: Historical Overview, Major Accomplishments, Current Status; Jordi Roglans-Ribas, Director of the Nuclear Engineering Division, Material Management and Minimization (M^3) Program Manager, ANL
- Risk-Based Management of Programs and Projects with Technical Uncertainties; Dave Maloney, Emeritus Technology Fellow, CH2MHill

- Discussion and Briefings on the Conversion of MURR Fuel; Ralph Butler, Executive Director of the University of Missouri Research Reactor (MURR) Center
- Highlights of Findings and Recommendations from the Independent Strategic Review of the M^3 Program; John Marra, Savannah River National Laboratory, Co-chair of M^3's Independent Strategic Review
- High Flux Isotope Reactor (HFIR) Fuel Development Effort; Michael Itamura, Acting Technical Lead for Fuel Fabrication Capability Pillar, M^3 Office, Sandia National Laboratories/National Nuclear Security Administration
- Critical Success Factors for Managing High Risk Programs; William Madia, Stanford University, Co-chair of M^3's Independent Strategic Review

OTWOCK-ŚWIERK, POLAND, MAY 5, 2015

- National Centre for Nuclear Research (in Polish, NCBJ); Grzegorz Wrochna, Director of NCBJ
- History of MARIA conversion; Marek Migdal, Neutronic Calculations Specialist, NCBJ

GARCHING, GERMANY, MAY 7, 2015

- The Forschungs-Neutronenquelle Heinz Maier-Leibnitz-II reactor (FRM-II) Technische Universität München (TUM): Neutrons for Research, Industry and Medicine; Winfried Petry, Scientific Director, FRM-II
- Conversion Studies of Reactor Core FRM-II; Anton Röhrmoser and Harald Breitkreutz, FRM-II
- UMo Powder Production Process and Results; Rupert Schauer, FRM-II
- Simulating In-Pile Radiation by Swift Heavy Ion Irradiation; Hsin-Yin Chiang, FRM-II
- Materials Selection; Hsin-Yin Chiang, FRM-II
- KP Implantation into Iodine Irradiated Monolithic U-Mo/Al Systems; Tobias Zweifel, FRM-II
- Thermal Properties of Fresh and Spent U-Mo Fuels: An Overview; Tanja Huber, FRM-II
- Manufacturing of Monolithic LEU Targets for Mo-99 Production; Tobias Hollmer, FRM-II
- International Cooperation: TUM, HERACLES and U.S. DOE; Harald Breitkreutz, FRM-II

MOL, BELGIUM, MAY 8, 2015

- The Belgian Nuclear Research Centre: A Pioneer in Nuclear Research; Eric van Walle, Director-General, Studiecentrum voor Kernenergie· Centre d'Etudes Nucléaire (SCK·CEN)
- LEU UMo Dispersion Fuel: Past, Present, and Future—the Path to Fuel Qualification and Conversion; Sven Van den Berghe, Head of the Expert Group on Microstructural and Non-destructive Analysis, SCK·CEN
- BR2 Introduction and Conversion; Geert Van den Branden, SCK·CEN

PETTEN, THE NETHERLANDS, MAY 11, 2015

- NRG [Nuclear Research and Consultancy Group] Welcome; Niels Unger, NRG Managing Director
- Ten Years of LEU Fuel Use at the High Flux Reactor; Frodo Klaassen, HFR Fuel Management

GRENOBLE, FRANCE, MAY 12, 2015

- U.S. National Academy of Sciences Committee Visit to ILL; W. G. Stirling, Director, ILL
- ILL TOUTATIS Project (RHF Conversion); Yoann Calzavara, ILL
- HERACLES: Highly Enriched European Reactors Action for Their Conversion in a Low Enriched Solution; Yoann Calzavara, ILL
- PERSEUS; Yoann Calzavara, ILL

PARIS, FRANCE, MAY 13, 2015

- AREVA/CERCA Overview; Dominique Geslin, Director, Marketing & Sales, Research Reactor Fuel (CERCA)
- High Enriched Uranium Minimization in France; Pierre-Yves Thro, Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA)

WASHINGTON, DC, MAY 21, 2015

- Uranium Supply and Demand; Parrish Staples, Director, Domestic Uranium Enrichment Program, National Nuclear Security Administration (NNSA)
- Question and Answer Session with M^3; Chris Landers, M^3 Conversion Program Manager, NNSA

- Babcock & Wilcox Cost and Yield Review, NAS; Gunes Argon, Project Manager—Research Test Reactors, newly renamed Babcock and Wilcox Technologies (BWXT)

GAITHERSBURG, MD, MAY 22, 2015

- Welcome and Introduction of the NCNR as a National User Facility; Rob Dimeo, Director, NIST Center for Neutron Research (NCNR)
- Status and Planning for the NIST Reactor Conversion; Bob Williams, NCNR
- Panel Discussion with NCNR Representatives

OAK RIDGE, TN, JUNE 24–26, 2015

- Review of Research Reactor Fuel Development at the Korea Atomic Energy Research Institute (KAERI); Jong-Man Park, Project Manager of Plate-Type Research Reactor Fuel Development and Advanced High Performance Research Reactor Fuel Development Projects, KAERI
- Objectives and Constraints for Research Reactor Conversion Design: Assessing Alternatives; John Stevens, International Reactor Conversion Technical Lead and Manager of Research and Test Reactor Department, Argonne National Laboratory (ANL)
- Examples of Research Reactor Conversion Assessment of Alternatives; Benoit Dionne, Section Manager, Conversion Analysis and Methods, ANL
- Progress Toward Low Enriched Uranium (LEU) Fuel Conversion of the High Flux Isotope Reactor (HFIR); David Renfro, HFIR LEU Fuel Conversion Project Manager, Research Reactors Division, UT-Battelle, Oak Ridge National Laboratory (ORNL)
- The Fuel Fabrication Capability (FFC) Pillar in FY16 and Beyond: Applied Engineering & Demonstration; Jared Wight, FFC Technical Pillar Lead, Pacific Northwest National Laboratory
- Current Status of and Progress Toward Eliminating Highly Enriched Uranium Use in Fuel for Civilian Research and Test Reactors; Hollie Longmire, Program Manager for LEU Applications, Y12 National Security Complex
- Overview of Neutron Sources; Paul Langan, Associate Laboratory Director
- Important Missions Beyond Neutron Scattering at HFIR; Chris Bryan

MOSCOW, RUSSIA, JULY 13–14, 2015

- Meeting with representatives of the Russian Academy of Sciences (RAS): V. Fortov, B. Myasoedov, Y. Shiyan, V. Ivanov, S. Yudintsev, B. Zhuikov, and A. Diakov from the Center for Arms Control, Moscow
  - — Discussion topics: HEU Minimization Within Research and Test Reactors (general discussion) and HEU Minimization Within Medical Isotope Production (general discussion)
  - — Production of Medical Radionuclides in Russia and Prospective Isotope Program in Institute for Nuclear Research, Moscow-Troitsk, Boris Zhiukov
  - — Meeting at the RAS with President Fortov
- HEU Minimization Efforts Within Rosatom; Nikolay Arkhangelsky, Director of Research Reactors, Rosatom
- Russian Priorities in Civilian Nuclear Matters; Anton Khlopkov, Director of the Center for Energy and Security Studies

DIMITROVGRAD, RUSSIA, JULY 16–17, 2015

- Strategic Planning for Research Reactors of State Scientific Centre "Research Institute of Atomic Reactors"; Alexey Izhutov, Deputy Director of RIAR, and Alexander Tuzov, Director of RIAR
- A Comprehensive Analysis of the Technical Feasibility of the MIR. M1 Research Reactor Conversion to Low Enriched Uranium Fuel; S. Mainskov, RIAR
- Development of Low Enriched Uranium Targets for ^{99}Mo Production; V. Starkov, RIAR
- JCS SCC RIAR Radionuclide Production Capabilities for Nuclear Medicine; Rostislav Kuznetsov, Director of Radioisotopes and ^{99}Mo production, RIAR

VIENNA, AUSTRIA, JULY 27–29, 2015

- International Atomic Energy Agency (IAEA) Research Reactor Data Base (RRDB) Information on HEU Research Reactors and Critical Facilities; M. Voronov, F. Marshall, D. Ridikas, IAEA
- Status of U.S. HEU Facilities and DOE/NNSA Conversion Activities; Jeff Chamberlin, Director, Office of Conversion, and Brian Waud, M^3 Reactor Conversion Program, USA
- Status of Russian HEU Facilities; Nikolay Arkhangelsky, Director of Research Reactors, Rosatom

- Status of French HEU Facilities; Pierre-Yves Thro, Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), France
- Status of UK HEU Facilities; Richard Hardiman, Head of Programme, Global Threat Reduction Programme, UK
- Civilian Reactor Facilities That Operate Using HEU Fuel; James (Jim) Matos, Argonne National Laboratory, USA

SITE VISITS

- February 26, 2015: Visit to ATR, ATR-C, and TREAT, Idaho National Laboratory
- April 16, 2015: Visit to University of Missouri Research Reactor
- May 5–13, 2015: Visits to
  - MARIA reactor, Otwock-Świerk, Poland
  - Forschungs-Neutronenquelle Heinz Maier-Leibnitz Reactor (FRM-II), Garching, Germany
  - Belgium Reactor-2 (BR2), Mol, Belgium
  - High Flux Reactor (HFR), Petten, Netherlands
  - Institut Laue-Langevin (ILL), Grenoble, France
- May 20, 2015: Visit to BWXT, Lynchburg, VA, USA
- May 22, 2015: Visit to National Institute of Standards and Technology (NIST) Center for Neutron Research, Gaithersburg, MD, USA
- June 25, 2015: Visits to High Flux Isotope Reactor (HFIR) Facility, Oak Ridge National Laboratory (ORNL), the Spallation Neutron Source, and Y-12 Fuel Fabrication Facility, Oak Ridge, TN, USA
- July 16–17, 2015: Visit to Joint Stock Company "State Scientific Center—Research Institute of Atomic Reactors"(JSC "SSC RIAR" or simply "RIAR"), Dimitrovgrad, Russia

Appendix D

Acronyms

ADS	Accelerator-driven system
AECL	Atomic Energy of Canada Limited
AFIP	ATR full-size plate in center flux trap position
ANL	Argonne National Laboratory
ATR	Advanced Test Reactor
ATR-C	Advanced Test Reactor Critical Facility
ATR NSUF	Advanced Test Reactor National Scientific User Facility
BWXT	Babcock and Wilcox Technologies
BR2	Belgian Reactor II (SCK·CEN, Mol, Belgium)
CA	Critical assemblies
CEA	Commissariat à l'Energie Atomique et aux Energies Alternatives
CEFR	China Experimental Fast Reactor
CERCA	Compagnie pour l'Etude et la Réalisation de Combustibles Atomiques
CFR	Code of Federal Regulations
CIAE	China Institute of Atomic Energy
cm	Centimeter
CNEA	Argentine National Commission of Atomic Energy
CNL	Canadian Nuclear Laboratories
CP-1	Chicago Pile-1
DOE	U.S. Department of Energy

DPRK	Democratic People's Republic of Korea
EPA	U.S. Environmental Protection Agency
ESS	European Spallation Source
FD	Fuel development
FDP	Fuel Data Provider (see Appendix E)
FFA	Federal facility agreement
FFC	Fuel fabrication capability
FMWG	Fissile Material Working Group
FNR	Ford Nuclear Reactor
FP-1 and FP-2	Full-sized fuel plate test-1 and test-2
FRM-II	Forschungs-Neutronenquelle Heinz Maier-Leibnitz-II
FY	Fiscal year
GE	General Electric
GE-NTR	General Electric Nuclear Test Reactor
GTRI	Global Threat Reduction Initiative
GTRP	Global Threat Reduction Program
HAMP	HANARO Mini-Plate
HANARO	High-Flux Advanced Neutron Application Reactor (Deokjin-dong)
HERACLES	Highly enriched European Reactors Action for their Conversion in a Low Enriched Solution
HEU	Highly enriched uranium
HFIR	High Flux Isotope Reactor (Oak Ridge)
HFR	High Flux Reactor (Petten)
HPRR	High performance research reactor
HT^3R	High-Temperature Teaching & Test Reactor
IAEA	International Atomic Energy Agency
IB	Ice breaker
IBR2M	Induced Bed Reactor–2M
ID	Identification (See Appendix F)
IGORR	International Group on Research Reactors
IL	Interaction layer
ILL	Institut Laue-Langevin (Grenoble)
in.	Inch
INFCE	International Nuclear Fuel Cycle Evaluation
INL	Idaho National Laboratory
INVO	Iraq Nuclear Verification Office
IPFM	International Panel on Fissile Materials

IRE	Institute for Radio Elements
IREN	Intense Resonance Neutron pulsed source
IRIS	International Reactor Innovative and Secure
IRT	In-Reactor Thimble (Fast Test Reactor)/Iraqi Reactor
ISR	Independent strategic review
IVV	Water-cooled, water-moderated (Russian acronym)
JHR	Jules Horowitz Reactor (CEA-Cadarache)
JMTR	Japan Materials Testing Reactor (Oarai)
JSC "SSC RIAR"	Joint Stock Company State Scientific Center—Research Institute of Atomic Reactors
KAERI	Korea Atomic Energy Research Institute
kg	Kilogram
KJRR	Ki-Jang Research Reactor
km/s	Kilometer per second
KUCA	Kyoto University Critical Assembly
kW	Kilowatt
LEONIDAS	Low Enriched Option Network Initiative for the Development of a European Appropriate Solution
LEU	Low enriched uranium
LITR	Low-intensity testing reactor
µm	Micrometer
M^3	Material Management and Minimization ("M-cubed"), also MMM
MBIR	Multipurpose sodium-cooled fast neutron research reactor (Russian acronym)
MIR	Modernized international reactor
MIT	Massachusetts Institute of Technology
MITR-II	Massachusetts Institute of Technology Reactor (Boston)
MNSR	Miniature Neutron Source Reactor
MOX	Mixed oxide fuel
MP	Mini-plate
MTR	Materials test reactors
MURR	University of Missouri Research Reactor (Columbia)
MW	Megawatts
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
N/A	Not applicable
NAA	Neutron activation analysis

NAS	National Academy of Sciences, now the National Academies of Sciences, Engineering, and Medicine
NBSR	Neutron Beam Split-core Reactor
NCBJ	Narodowe Centrum Badan Jadrowych (National Center for Nuclear Research)
NCCP	Novosibirsk Chemical Concentrates Plant
NCNR	NIST Center for Neutron Research
NIKIET	Research and Development Institute of Power Engineering (Nauchno-issledovatel'skii institut energotekhniki)
NIST	National Institute of Standards and Technology
NNSA	National Nuclear Security Administration
NRG	Nuclear Research and Consultancy Group
NSC	National Security Council
NSS	Nuclear Security Summit
NSUF	Nuclear Science User Facility
NTD	Neutron transmutation doping
NTI	Nuclear Threat Initiative
NV	Naval reactor
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Research Reactor
OSTP	Office of Science and Technology Policy
PIE	Post-irradiation examination
PNNL	Pacific Northwest National Laboratory
PR	Pulsed reactor
PVD	Physical vapor deposition
RAS	Russian Academy of Sciences
RERTR	Reduced Enrichment for Research and Test Reactors
RHF	Réacteur à Haut Flux (Grenoble)
RIAR	Research Institute of Atomic Reactors (Dimitrovgrad)
RR	Research reactor
RRDB	Research Reactor Database
RRFM	European Research Reactor and Fuel Management Conference
RRRFR	Russian Research Reactor Fuel Return (Program)
SAFARI	South African Fundamental Atomic Research Installation

SCK·CEN	Studiecentrum voor Kernenergie·Centre d'Etudes Nucléaire
SLOWPOKE	Safe Low-Power Kritical Experiment
SNS	Spallation Neutron Source
SS	Steady-state reactor
TAPIRO	TAratura PIla Rapida a potenza 0
TEM	Transmission electron microscopy
TOUTATIS	Traitement Optimisé de l'Uranium et Thermique Améliorée pour une Technologie Intégrant la Sûreté
TREAT	Transient Reactor Test Facility
TRIGA	Training, Research, Isotopes, General Atomics
TUM	Technische Universität München
U.K.	United Kingdom
UM	University of Michigan
USNRC	U.S. Nuclear Regulatory Commission
U.S.	United States
USHPRR	U.S. high performance research reactor
VENUS	Vulcan Experimental Nuclear Study
VIC	Vienna International Center
VNIIEF	All-Russian Scientific Research Institute of Experimental Physics (Vsesoyuznyy nauchnoissledovatel'skiy institut eksperimental'noy fiziki)
vol.	Volume
W	Watt
W-HEU	Weapon-grade highly enriched uranium
wt	Weight
Y-12	Y-12 National Security Complex
YTC	Years to conversion
ZPTF	Zero Power Test Facility

Appendix E

Joint International Atomic Energy-Academies Meeting Synopsis

A joint International Atomic Energy Agency (IAEA)–National Academies of Sciences, Engineering, and Medicine ("Academies") meeting was held July 27–29, 2015, at the IAEA in Vienna. The purpose of the meeting was to bring together nuclear research reactor experts from across the world to identify a list of civilian research and test reactors currently operating with highly enriched uranium (HEU) fuel.

This meeting was motivated by the realization that the Academies and IAEA were conducting concurrent and similar efforts. This Academies committee was charged by the U.S. Congress to review the status of research reactor conversion from HEU to low enriched uranium (LEU) fuel worldwide; one of the committee's tasks was to develop a list of civilian research reactors using HEU fuel. At the same time, the IAEA continued its efforts to gather information on the operational and fuel status of research reactors to better assist its member states. The two organizations combined their efforts to extend the breadth of participating experts and to bring a unified focus to developing one list. The meeting was open to the public; this synopsis provides the public report of the meeting discussions and the finalized list of civilian research reactors currently operating with HEU. The meeting agenda can be found at the end of the synopsis.

Drs. Borio di Tigliole (head of the IAEA's Research Reactor Section) and Phillips (chair of the Academies committee) welcomed the participants, both noting the importance of the meeting to generate a single, authoritative list.

Joanie Dix, the IAEA host, presented information on the scope and purpose of the meeting. The meeting objectives were to present, compare,

discuss, and review publicly available data regarding international civilian facilities operating with HEU. The meeting participants were instructed to generate an agreed-upon list of civilian research reactors currently operating with HEU. Two important points were raised by participants: the list will not be a de facto list of candidates for conversion or shutdown, and it will be made publicly available.

The first day of the 3-day meeting introduced the participants, defined the criteria for a reactor to be included in the list, and allowed experts from different countries to provide briefings on the status of research reactors worldwide.[1] At the conclusion of the first day, a draft list of reactors was produced based on presentations provided. Day 2 allowed participants to review the draft list at a detailed level. By applying the criteria developed the previous day, an updated draft list was produced. Day 3 included a review of the second draft list and acceptance of a final list.

Rules on the discussion of sensitive information were reviewed and agreed upon before the presentations and discussions began. Specific topics that were to be avoided, generally arising by virtue of the sensitivities surrounding HEU, were identified. It was noted that detailed discussion of reactors with a sole defense-related (or military-related) mission and details related to their use would not be discussed.[2] The group also decided that percentages of enrichment and amounts of HEU at a given research reactor facility would also not be discussed.

CRITERIA FOR INCLUSION ON THE LIST

A set of criteria for a research reactor facility to be included on the list was developed following the scope and purpose presentation and evolved over the course of the 3-day meeting as the attendees applied the criteria. The decisions on criteria appearing below in Table E.1 are the final criteria agreed upon by the participants.

The list has the following columns:

"Country":	the country in which the research reactor facility is operated
"City":	closest city to the facility operating the reactor

[1]Experts from the countries with the largest number of research reactors currently using HEU fuel (France, Russia, and the United States) were in attendance, but not all countries were represented. To review worldwide research reactors not discussed by individual experts, Dr. James (Jim) Matos provided a summary. The content of his list was further verified by publicly available documents.

[2] Reactors with mixed civilian and military missions were to be included in the list and are discussed further below.

TABLE E.1 Criteria for Inclusion or Exclusion from the List

	Included in the List	Excluded from the List
Type of research reactor facilities	Steady state reactors	Propulsion reactors (ice breakers, naval propulsion reactors)
	Critical assemblies	Plutonium-fuel reactors
	Subcritical assemblies	Naval prototypes
	Pulsed reactors	Tritium production reactors
	Accelerator-driven sources	
Mission of reactor	Sole civilian use	Sole military use
	Mixed civilian/military use ("dual use")[a]	
Operational status	Currently operating reactors	Decommissioning or decommissioned[b]
	Reactors not currently operating but with HEU fuel on site that is currently licensed	Not currently operating with HEU fuel on site that no longer is licensed

[a] See "Discussions on Complicated Issues," below.
[b] By definition of a decommissioning/decommissioned facility, all fuel has been removed from the site.

"Facility": name of the facility that operates the reactor, including its acronym

"Name": name of the reactor, including its acronym (if applicable)

"Reactor type": shortened for "research reactor facility type" (see Table E.1 for the list of included reactor types)

"Power": if listed as steady state, then the nominal power level (the maximum power level for which the reactor was designed to operate) is shown; the group agreed to make no entry for power level for pulsed reactors or critical and subcritical assemblies

"Notes": additional information related to an expected imminent change in status (e.g., if reactor status is expected to change within the next 2 years) or operating conditions of the reactor (e.g., reactors that are currently operating at power levels that differ from the nominal value)

"IAEA RRDB number": a unique identifier applied by the IAEA Research Reactor Database (RRDB) administrators; "N/A" was used when an IAEA RRDB number does not exist for a given facility

It was acknowledged, based on imminent conversions and shutdowns, that the list from the 2015 consultancy meeting will be a snapshot in time and will soon be out of date. The attendees agreed that it would be useful to hold periodic consultancies (approximately every 2 years) to update the list (e.g., the IAEA has held two previous consultancies, one in 2006 and the other in 2008, to generate similar lists).

DISCUSSIONS ON COMPLICATED ISSUES

The criteria and definitions determined above were applied to all of the research reactor facilities presented by the speakers as well as additional research reactor facilities identified by other meeting participants. Several complicated topics, for which the criteria were insufficient, arose and generated repeated discussion throughout the 3-day meeting. These topics presented difficult issues for determining whether or not to include a reactor on the list. The topics and discussions included the following.

Dual-Use Facilities

Dual-use reactors, used for both civilian and military applications, are a challenging topic because of sensitivities related to the details of military use. Therefore it was proposed that the designation of "civilian" would include both sole civilian and dual civilian and military use; participants decided to remove the "dual-use" designation to avoid the release of sensitive information. As such, the list does not include a heading that indicates civilian or dual use for each reactor.

Participants agreed that the designation of "civilian use" would be determined by experts of the country owning the reactor presenting at this meeting and would be further validated by the identification of the regulating and/or operating body and through publicly available information. However, the expert participants were not considered as officially representing member states. Therefore, the information supplied by their presentations is not considered official correspondence from the member states. These ground rules were applied consistently across the research reactor facilities of all countries.

Plutonium (Pu)-Fueled Reactors

Plutonium-fueled reactors were excluded from the final list, but participants acknowledged the proliferation risks associated with Pu-fueled reactors. Experts cited several examples including the IBR2M and IREN reactors in Russia or the JOYO and MONJU mixed oxide (MOX)-fueled reactors in Japan, but did not attempt to produce a comprehensive list.

Critical Assemblies

Critical assemblies (CAs) or subcritical assemblies with sets of cores containing different fuels (including both LEU and HEU) are challenging, because the cores can be easily reconfigured. Adding to the complexity is the fact that HEU can be inserted into the critical or subcritical assembly as a test object. To determine whether a specific critical or subcritical assembly should be on the list, the participants decided to consider whether or not the licensed cores contained HEU. The group agreed that an HEU test element was not a fuel element and therefore would not be the determining factor for inclusion on the list.

As an example, Chaika and Filin are critical assemblies that are no longer operating and have no active licenses, but HEU fuel remains stored on site. Neither is included in the list, because there are no active licenses. These types of assemblies would be included in a minimization effort but excluded in a list of currently operating reactors.

Final examples are not critical assemblies but are still relevant to this topic: the Jules Horowitz Reactor (JHR) and the Transient Reactor Test Facility (TREAT) reactor. Although JHR is expected to initially use HEU fuel until a qualified high-density LEU fuel is available, it is not currently operating, and there is no HEU on site. Therefore, JHR is not on the list. Alternatively, TREAT, a U.S. research reactor, is also not operational, but HEU fuel is on site. TREAT is on the list.

SUMMARY OF PRESENTATIONS AND DISCUSSIONS

Presentations and related discussions occurring throughout the 3-day meeting are summarized below. For consistency and clarity, all of the summaries follow the same format and structure: an accounting of the number and type of reactors identified for each country or countries followed by an overview of the discussions on specific research reactors associated with specific countries. The topic of the first presentation, an overview of the content of the IAEA Research Reactor Database, did not lend itself to that format.

IAEA Research Reactor Database (RRDB)—Information on HEU Research Reactors and Critical Facilities

The current IAEA RRDB contains information on more than 770 reactors worldwide. Information contained in the database has been provided to the IAEA by a number of sources. Data may have been provided by the facility operator, official agencies or organizations (e.g., the U.S. Nuclear Regulatory Commission or the Russian State Atomic Energy Corporation [Rosatom]) for facilities under their purview, public government releases, and public documents.[3] Other official documents, for example, the results from this meeting, may be used to update the IAEA RRDB, if the member states agree to the changes identified.

Information contained in the database is divided into two major parts: the reactor section (publicly accessible) and the fuel section (limited access). The reactor section may be accessed by the general public; edits can only be made by someone designated by the facility (an IAEA database administrator). At the request of member states, the IAEA restricted details on fuel type and amounts (and other information) from public access. Therefore, fuel section details can only be accessed and edited by one designated Fuel Data Provider (FDP) for each member state.[4] The fuel section of the database contains details on core data, fuel and inventory, storage, concerns, and fuel-cycle management planning.

Some information within the database may be out of date and potentially inaccurate. For example, some of the more than 700 reactors have a sole military mission, and as such they should not be included in the IAEA database. Several participants noted that the inclusion of these reactors is creating confusion, and therefore they should not be listed. The IAEA database administrators agreed that some information is potentially out of date, but that changes to the database could only be accepted from the sources listed above. They encourage member states to correct these inaccuracies and provide regular updates to ensure the accuracy of the IAEA RRDB.

United States

Summary

8 (total) research reactor facilities currently using HEU fuel
6 high performance research reactors (HPRRs)

[3] See, for example, the Directory of Research Reactors Worldwide, IAEA, STI/PUB/1071, 1998 or N. V. Arkhangelsky, I. T. Tretiyakov, and V. N. Fedulin, Nuclear Research Facilities in Russia, OJSC NIKIET, Moscow, 2012.

[4] The IAEA RRDB administrators have access to all of the member states' fuel section details; these details cannot be (and are not) shared with other member states.

2 research reactors
U.S. military reactors are not included in these totals

The U.S. conversion program has recently been reorganized under the new Office of Material Management and Minimization (M^3). The three main activities, or pillars, of the M^3 office are conversion, removal, and disposal ("disposal" replacing the "secure" pillar from the Global Threat Reduction Initiative [GTRI], the previous home of the conversion program). The Office of Conversion includes research reactor conversion and molybdenum-99 (^{99}Mo) production.

A total of 28 U.S. civilian research reactors have been candidates for HEU to LEU conversion; 20 have converted and/or shut down. Of the 8 remaining, 6 await conversion until a new high-density LEU fuel is qualified.[5] The M^3 Office of Conversion is working to develop the UMo monolithic fuel needed to convert these reactors while maintaining performance. The first conversions are expected in 2025 (see Chapter 4, MITR-II [Massachusetts Institute of Technology Reactor] and NBSR [Neutron Beam Split-core Reactor]). The conversion of High Flux Isotope Reactor (HFIR) will take the longest because of the complexity of its fuel design; its conversion is scheduled to take place in 2032.

Two additional U.S. research reactors currently using HEU fuel are the Transient Reactor Test Facility (TREAT, Idaho National Laboratory) and General Electric Nuclear Test Reactor (GE-NTR, California). The TREAT reactor is currently not operational, but is expected to restart by 2018 with HEU fuel (a graphite-based fuel type that requires new LEU fuel to be developed). TREAT will convert after a new LEU has been developed and tested. TREAT will be used to test accident-tolerant fuels (no military applications). Until recently, conversion discussions between the conversion program and the GE-NTR reactor operators have not been able to proceed. However, after initial discussions earlier this year, GE-NTR reactor operators have expressed interest in conversion.

The M^3 Office of Conversion maintains a list of research reactors worldwide that currently use HEU fuel and are under consideration for conversion. Recently, changes to the scope of M^3's conversion list have been proposed (including the removal of Russian military reactors). This meeting was expected to further help to define the scope of M^3's list.

M^3's definition of *conversion* was discussed. M^3 considers a reactor "converted" if it meets three criteria: licensing for LEU fuel has been

[5] They are Advanced Test Reactor (ATR), Advanced Test Reactor Critical Facility (ATR-C), Massachusetts Institute of Technology Reactor (MITR-II), Neutron Beam Split-core Reactor (NBSR), University of Missouri Research Reactor (MURR), and the High Flux Isotope Reactor (HFIR).

completed, a clear commitment by country and operators has been made, and the first LEU assembly has been inserted. The IAEA research reactor database administrators noted their definition for conversion is a full (completely converted) core of LEU fuel.

Russia

Summary

71 civilian research reactor facilities
43 HEU civilian research reactor facilities (currently using or previously used HEU fuel)

Of the 43 facilities, 24 are steady state or pulsed reactors, 18 are critical assemblies, and 1 is a subcritical assembly. Some of these reactors were originally military reactors, but their use has changed over the years to include civilian applications (per agreements on the discussion of sensitive information, the ratio of the mix between civilian and military use was not discussed). Additionally, these reactors are now considered "civilian" because they are regulated by Rostechnadzor (the civilian nuclear regulatory agency). Also, 9 of the 43 civilian research reactor facilities that previously used HEU fuel are undergoing decommissioning, and as such, the HEU fuel has been removed.

Steady State and Pulsed Reactors

A total of 24 steady state and pulsed research reactors are eligible for the list: 16 operating reactors, 7 undergoing decommissioning, and 1 under construction but beginning operations. BARS-4 and BARS-6 (pulsed reactors) were originally military reactors but are now used for civilian applications. The reactors undergoing decommissioning are listed for completeness (even though some of them are considered propulsion reactors): Argus, BR-10, 27/VM, 27/VT, TVR, Gamma, and MR.[6] Of these seven reactors, the Gamma reactor was originally used as a military reactor but became a civilian facility before it was decommissioned. The Argus reactor converted to LEU fuel in 2014. The PIK reactor, the one reactor that is under construction, is currently licensed to operate and is operating at low power (100 W) but is expected to operate up to 100 MW in the future.

[6] As mentioned previously in the synopsis, decommissioned reactors or reactors undergoing decommissioning should not be included in the list of operating reactors, as all fuel has been removed.

Critical Assemblies

Eighteen civilian critical assemblies (CAs) are currently operating with HEU fuel: 15 operating/operational, 2 undergoing decommissioning, and 1 undergoing modernization. From this list of critical assemblies, Rosatom manages seven operational CAs and one undergoing modernization. The number of critical assemblies managed by Rosatom has significantly decreased over the past several years. Ten years ago, there were more than 10 CAs in Obnisnk; now there are only 3. Improvements to computer simulation codes have obviated the need for many of these CAs.

Some of the CAs have both LEU and HEU cores; they remain on the list because they are currently licensed for HEU use (e.g., ST-659 and ST-1125, and see "Discussions on Complicated Topics"). Additionally, ST-659 and ST-1125 were used in development of military reactors. They are now managed by Rosatom and are used for civilian applications including investigations of fuel for pressurized water reactors (PWRs) and testing of KLT-40 reactors (civilian icebreaker reactors).

Ten operational civilian CAs (with two undergoing decommissioning) are not managed by Rosatom. Of these, SF-1 and SF-7 were developed for propulsion systems but were later used for civilian purposes. Aksamit was also originally a military reactor but is now used for civilian applications. Aksamit uses the RP-50 assembly (which is an HEU assembly).

Highlights from further discussions on specific Russian reactors included the following:

- The licensing of the facility defines the assemblies and cores that may be used. For example, RP-50 is not licensed separately, but it is included in Aksamit's license. If Aksamit is not licensed, then RP-50 cannot be used. Similarly, the license for Filin research reactor facility in Belarus would include its associated assemblies (Chaika, for example).
- Joint Stock Company State Scientific Center—Research Institute of Atomic Reactors (JSC "SSC RIAR's") RBT-6 and -10/2 should be counted as two additional facilities separate from SM-3 (even though both use irradiated fuel from SM-3), because they are licensed separately.
- Propulsion reactors can have a variety of missions, including naval prototype testing, space propulsion, training, research facilities used to test fuel, and different categories of propulsion-related research. The last item is relevant to the list. For example, NARCISS-M2 performs research on space propulsion and appears on the list.

France

Summary

France has constructed a total of 38 civilian research reactor facilities of which:

16 were constructed initially using LEU fuel
22 were constructed initially using HEU fuel

Of the 16 civilian facilities that started up with LEU fuel, 14 have shut down and 2 remain (Eole and Masurca), and one uses HEU fuel (Masurca). Of the 22 civilian facilities initially using HEU fuel, 16 have shut down, 3 have converted to LEU fuel, and 3 remain operational with HEU fuel (Orphée, Minerve, and Neutronographie Phénix). Not included in this accounting is the Réacteur à Haut Flux/Institut Laue-Langevin (RHF/ILL) in Grenoble that uses HEU fuel. In total, five civilian research reactor facilities are currently operating with HEU fuel in France.

Highlights from further discussions on specific French reactors included the following:

- Masurca and Eole are critical assemblies. Masurca uses an HEU core. The Eole critical assembly generated a discussion on the availability and type of cores used for experiments. Eole currently uses an LEU core, and French experts attending the meeting have asked that Eole be removed from the list. However, it remains unclear whether a licensed HEU core remains on site.
- One reactor (the Jules Horowitz Reactor under construction) is expected to begin operations in 2020 with HEU fuel (enriched to 27 percent), but it will convert when a high-density LEU fuel becomes qualified. Because JHR is not yet operational and there is no fuel on site, it was not included in the list. Participants asked whether JHR operators would consider using a high-density LEU silicide fuel. The option would have to be thoroughly investigated, because a 10 percent loss in performance was estimated if this path were followed.
- Several participants had questions about the ZEPHYR reactor, which is in an early design stage and does not yet exist.

The high-density LEU uranium molybdenum (UMo) dispersion fuel was also discussed. The LEU fuel development program has cost approximately €160 million in Europe, and it is estimated that it will cost several tens of millions more to qualify the fuel. There is some concern about the future price of the high-density LEU fuel, because it is not expected to be equiva-

lent to or cheaper than the HEU fuel. In 15 years, when the fuel is likely to be qualified, several existing reactors may be closed, which makes the economic argument for new fuel fabrication increasingly difficult. Another participant noted that the U.S. perspective on the economics of LEU fuel development and commercialization (the United States is pursuing UMo monolithic LEU fuel) is that it is not a business venture but for the public good to be paid for by the government.[7]

United Kingdom

Summary

No operating civilian research reactors are currently using HEU fuel in the United Kingdom (U.K.).

The last civilian HEU research reactor facility, CONSORT, was shut down in 2012, its fuel was removed and transported to Sellafield in 2014, and decommissioning is expected to be completed in 2021.

The U.K. remains a strong supporter of nonproliferation efforts to convert research reactors and remove HEU fuel by providing international assistance through its Global Threat Reduction Program (GTRP). Recent projects with other nations include the Ukraine (linear accelerator project) and Uzbekistan (Institute of Nuclear Physics VVR-SM research reactor and defueling of Joint Stock Company Foton's IIN-3M research reactor).

Other Countries[8]

Summary

A total of 24 civilian research reactors using HEU fuel exist outside of the United States, Russia, France, and the United Kingdom. After conclusion of the meeting, two reactors were declared as being shut down with HEU fuel removed (the Safe Low-Power Kritical Experiment [SLOWPOKE] reactor in Jamaica and the reactor in Basel, Switzerland). The current total numbers of civilian research reactors operating in each continent are:

[7] NRC. 2012. Progress, Challenges, and Opportunities for Converting U.S. and Russian Research Reactors. Washington, DC: The National Academies Press.

[8] Dr. Matos, an internationally recognized expert on conversion of reactors and the status of currently operating facilities, was invited to provide a summary of the remaining civilian research reactors still operating with HEU fuel throughout the world.

16 are in Asia (including the Middle and Far East)
1 is in North America, excluding the United States
5 are in Europe, excluding France
2 are in Africa

Highlights from further discussions on specific Asian reactors included the following:

- Within Asia, four research reactors are operating in the Middle East: one each in Iran, Pakistan, Syria, and Israel. The Israeli research reactor (IRR-1) is expected to be shut down; a new facility is planned to take over the functions of IRR-1. The other three reactors are Chinese-supplied Miniature Neutron Source Reactors (MNSRs).
- Twelve research reactors are in the Far East. China operates four reactors using HEU fuel; two of the four are MNSRs, of which one is scheduled to convert in 2015.[9] The China Experimental Fast Reactor (CEFR)[10] is considered a prototype fast power reactor. Although it is connected to grid, it is considered a research reactor using HEU. The Zero Power Fast (ZPR Fast) reactor at the China Institute of Atomic Energy (CIAE) is a fast critical assembly.[11]
- Japan operates four research reactors using HEU fuel.[12] Japan's Tokai plans to use an accelerator-driven source using LEU fuel to burn fuels with high-actinide content. The current plan is for the fast critical assembly facility at Tokai to ship its HEU fuel to the United States and to construct a critical facility for the accelerator-driven system (ADS) using LEU fuel. The Kyoto University Critical Assembly (KUCA) facility generated a long discussion. The facility operates a total of three separate reactors with two cores (one wet, the other dry). Because there is fuel for only two reactors (the two dry-core reactors share the same fuel), it was agreed that the list would show two reactors: the KUCA Wet Core[13] and the KUCA Dry Core. The participants justified separating the facilities

[9] See the following links for more information: https://www.iaea.org/OurWork/ST/NE/NEFW/Technical-Areas/RRS/mnsr.html and http://www-pub.iaea.org/MTCD/Publications/PDF/P1575_CD_web/datasets/abstracts/E3RoglansRibas.html.

[10] See http://www.ciae.ac.cn/eng/cefr/index.htm.

[11] Feng Shen, The Present Status and Future Potential Applications of RRs in CIAE, Proceedings of the 5th International Conference on the Frontiers of Plasma Physics and Technology, IAEA TECDOC (CD-ROM) 1713, Singapore, April 18–22, 2011.

[12] See http://www.nti.org/analysis/articles/civilian-heu-japan/.

[13] *Wet core* means water moderated.

because conversion of these reactors could potentially take place separately. It was noted that the IAEA and Japan count KUCA as one facility.[14]

- Kazakhstan has three reactors using HEU fuel: IGR and IVG-1M in Kurchatov and WWR-K at Almaty. The IGR reactor is a graphite-fuel-based reactor (similar to TREAT in the United States).[15] At the time of the meeting, the WWR-K reactor had recently defueled in preparation for conversion to LEU fuel.[16]
- Two North Korean (DPRK) research reactors generated a short discussion on their origin; both appear on the list despite significant uncertainties.[17] The DPRK's steady state reactor (DPRK-IRT) uses fuel similar to Libya's reactor, which has converted to LEU fuel. The status of the critical assembly (DPRK-IRT CA) is not known; it was decided to keep this reactor on the list until it can be confirmed as decommissioned or converted. The DPRK-IRT CA may be DPRK designed. It is currently not clear whether it is using HEU or LEU fuel. Although it is known that this facility existed previously, it is also not clear whether it still exists.

Highlights from further discussions on specific North American research reactors, excluding those in the United States, included the following:

- In North America, two operating research reactors currently use HEU fuel in Canada. Canada is seeking funding to complete its conversions. The SLOWPOKE research reactor in Jamaica recently converted with assistance from the M^3 Office of Conversion.[18]

Highlights from further discussions on specific European research reactors, excluding those located in France, included the following:

[14] H. Unesaki, T. Misawa, T. Sano, K. Nakajima, and J. Roglans-Ribas, On the Feasibility Study for Utilization of Low Enriched Uranium Fuel at Kyoto University Critical Assembly (KUCA), Proceedings of the 33rd International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR 2012), Santiago, Chile, October 23–27, 2011.

[15] See http://www.nnc.kz/en/O-predpriyatii/experimental_units/igr.html.

[16] Y. Goncharov, A. Enin, I. Zaporozhets, P. Chakrov, S. Gizatulin, F. Arinkin, and Y. Cherepnin, Low Enriched Uranium Fuel for VVR-K Reactor, Proceedings of the 2013 European Research Reactor Conference (RRFM 2013), St. Petersburg, Russian Federation, April 21–25, 2013.

[17] See also the following links: http://www.nti.org/facilities/767/ or http://cns.miis.edu/archive/country_north_korea/nuc/chr4789.htm.

[18] Shortly after the IAEA–Academies meeting, the NNSA announced the conversion and removal of the SLOWPOKE reactor and that the Caribbean was HEU-free. See http://nnsa.energy.gov/mediaroom/pressreleases/nnsa-removes-u.s.-origin-heu-jamaica-makes-caribbean-heu-free.

- Within Europe, there are six research reactors: two in Belarus, two in Belgium, and one each in Germany and Italy (a research reactor in Switzerland recently shut down and its HEU fuel has been removed[19]).
- A participant asked about the fuel from the Kristal facility in Belarus. The Kristal reactor has been shut down, but the fuel remains in Belarus. There is technical "buy-in" from the Belarussians for HEU removal, but progress toward fuel removal remains stalled because of political issues.
- The VENUS reactor is one of the two reactors in Belgium currently operating with HEU fuel. The VENUS reactor uses HEU fuel on loan from Masurca in France. The Belgians plan to return the HEU fuel to France upon completion of the VENUS experiments (expected in 2022 or 2023). Belgian Reactor II (BR2), a high performance research reactor, is the other Belgium reactor currently using HEU fuel.
- The researchers at the Forschungs-Neutronenquelle Heinz Maier-Leibnitz-II (FRM-II) reactor in Germany are studying ways to reduce the fuel enrichment percentages while maintaining reactor performance.[20] The TAPIRO reactor in Italy is difficult to convert to LEU (conversion feasibility is being studied at Argonne National Laboratory),[21] because the core is composed of a small stack of UMo disks. The core and size (approximately the size of a small water pitcher) make conversion difficult, because current available options would increase the size of the core by a factor of five to six times, which would require a facility redesign. In addition, the spectrum of neutrons is important to maintain in order to meet its mission.
- Finally, the two research reactors in Africa are Chinese-designed MNSRs and are located in Ghana and Nigeria.[22]

[19] See http://www.world-nuclear-news.org/RS-Swiss-research-reactor-fuel-returned-to-USA-1609154.html.

[20] See https://www.frm2.tum.de/en/the-neutron-source/reactor/fuel-development/faq-heu/.

[21] J. Roglans, GTRI Reactor Conversion Program Scope and Status, presented at the Academies Committee Meeting, October 23, 2014, Washington, DC, USA.

[22] A short discussion on the feasibility of conversion of many of the reactors is not included, because it is out of scope of the consultancy.

LIST OF CIVILIAN RESEARCH REACTORS CURRENTLY USING HEU FUEL

Based on the criteria established by the meeting participants as noted above, a list of 72 civilian research reactor facilities currently operating with HEU fuel is provided in Table E.2.

TABLE E.2 Civilian Reactor Facilities Operating on HEU Fuel, Alphabetical by Country

	Country	City	Site	Reactor
1	Belarus	Minsk	Sosny	Hyacinth/Giacint
2	Belarus	Minsk	Sosny	Yalina B
3	Belgium	Mol	SCK·CEN	BR2
4	Belgium	Mol	SCK·CEN	VENUS
5	Canada	Alberta	University of Alberta	SLOWPOKE AB
6	Canada	Saskatoon	Saskatchewan Research Council	SLOWPOKE SK
7	China	Beijing	CIAE	CEFR
8	China	Beijing	CIAE	MNSR-IAE
9	China	Shenzhen	Shenzhen University	MNSR-SZ
10	China	Beijing	CIAE	Zero Power Fast
11	DPRK	Yongbyon	Nuclear Research Institute Yongbyon	IRT-DPRK
12	DPRK	Yongbyon	Nuclear Research Institute Yongbyon	IRT-DPRK CA
13	France	Cadarache	CEA Cadarache	Masurca
14	France	Cadarache	CEA Cadarache	Minerve
15	France	Marcoule	CEA Marcoule	Neutronographie Phénix
16	France	Saclay	CEA Saclay	Orphée
17	France	Grenoble	ILL	RHF
18	Germany	Garching	TUM Garching	FRM-II
19	Ghana	Accra	National Nuclear Research Institute Accra	GHARR-1 (MNSR)
20	Iran	Esfahan	Esfahan Nuclear Technology Center	ENTC (MNSR)
21	Israel	Yavne	Soreq Nuclear Research Center	IRR-1
22	Italy	Casaccia	ENEA Casaccia	TAPIRO
23	Japan	Tokai-mura	JAEA Tokai	FCA

Nominal P, kW	Reactor Type	Notes	IAEA #
	Critical Assembly		BY-0009
	Subcritical Assembly		BY-0003
100,000	Steady State	Typically operated at 50,000-70,000 kW	BE-0002
	Fast Critical Assembly	Material on loan from Masurca	BE-0006
20	Steady State	Expected to shut down (applied for shutdown license)	CA-0011
20	Steady State		CA-0012
65,000	Prototype Fast Power Reactor		CN-0018
27	Steady State	To be converted to LEU by end of 2015	CN-0006
27	Steady State		CN-0013
	Fast Critical Assembly		CN-0003
8,000	Steady State		KP-0001
	Critical Assembly	Status and fuel type unknown	N/A
	Fast Critical Assembly		FR-0016
	Critical Assembly	Expected to shut down in 2019	FR-0003
	Critical Assembly	Expected to shut down in 2015	N/A
14,000	Steady State	Expected to shut down in 2019	FR-0022
58,000	Steady State		FR-0017
20,000	Steady State		DE-0051
27	Steady State	Conversion to LEU expected in 2016	GH-0001
27	Steady State		IR-0005
5,000	Steady State		IL-0001
5	Steady State		IT-0008
	Fast Critical Assembly		JP-0014

continued

TABLE E.2 Continued

	Country	City	Site	Reactor
24	Japan	Osaka	KURRI	KUCA (Dry Cores)
25	Japan	Osaka	KURRI	KUCA (Wet Core)
26	Japan	Osaka	AERI Kinki University	UTR Kinki
27	Kazakhstan	Kurchatov City	NNC-IAE	IGR
28	Kazakhstan	Kurchatov City	NNC-IAE	IVG-1M
29	Kazakhstan	Almaty	INP-Alatau	WWR-K
30	Nigeria	Zaria	Ahmadu Bello University (CERT)	NIRR-1 (MNSR)
31	Pakistan	Islamabad	PINSTECH	PARR-2 (MNSR)
32	Russia	Moscow	NRC KI	AKSAMIT
33	Russia	Moscow	NRC KI	ASTRA
34	Russia	Lytkarino	NIIP	BARS-4
35	Russia	Obninsk	IPPE	BARS-6
36	Russia	Obninsk	IPPE	BFS-1
37	Russia	Obninsk	IPPE	BFS-2
38	Russia	Dimitrovgrad	RIAR	BOR-60
39	Russia	Dimitrovgrad	RIAR	CA MIR.M1
40	Russia	Moscow	NRC KI	DELTA
41	Russia	Moscow	NRC KI	EFIR-2M
42	Russia	Gatchina	NRC KI	FM PIK
43	Russia	Obninsk	IPPE	FS-1M
44	Russia	Moscow	NRC KI	GIDRA
45	Russia	Moscow	NRC KI	IR-8
46	Russia	Moscow	MEPhI	IRT-MEPhI
47	Russia	Tomsk	TPU	IRT-T
48	Russia	Zarechny	IRM	IVV-2M
49	Russia	Obninsk	IPPE	K-1
50	Russia	Moscow	NRC KI	KVANT
51	Russia	Moscow	ITEP	MAKET
52	Russia	Dimitrovgrad	RIAR	MIR.M1

Nominal P, kW	Reactor Type	Notes	IAEA #
	Critical Assembly	1 facility with 3 reactors and 2 sets of fuel (one for wet core, one for dry cores)	
	Critical Assembly		JP-0018
0.001	Steady State		JP-0003
	Pulsed reactor		KZ-0002
72,000	Steady State	Sometimes listed as EWG-1	KZ-0003
6,000	Steady State	Conversion to LEU expected in 2016 (LEU fuel is on site). Sometimes listed as VVR-K.	KZ-0001
27	Steady State		NG-0001
27	Steady State		PK-0002
	Critical Assembly	RP-50 is part of AKSAMIT	RU-0026
	Critical Assembly		RU-0073
	Pulsed Reactor		RU-0046
	Pulsed Reactor	OKUYAN is part of BARS-6	RU-0040
	Fast Critical Assembly		RU-0063
	Fast Critical Assembly		RU-0064
60,000	Fast Reactor	Expected to shut down in 2020	RU-0027
	Critical Assembly		RU-0082
	Critical Assembly		RU-0079
	Critical Assembly		RU-0078
	Critical Assembly		RU-0025
	Critical Assembly		RU-0054
	Pulsed reactor	Sometimes listed as HYDRA	RU-0017
8,000	Steady State		RU-0004
2,500	Steady State		RU-0005
6,000	Steady State		RU-0014
15,000	Steady State		RU-0010
	Critical Assembly	Being refurbished	N/A
	Critical Assembly		RU-0072
	Critical Assembly	Research on special reactors	RU-0053
100,000	Steady State	Typically operated at 30,000-60,000 kW	RU-0013

continued

TABLE E.2 Continued

	Country	City	Site	Reactor
53	Russia	Moscow	NRC KI	NARCISS-M2
54	Russia	Moscow	NRC KI	OR
55	Russia	Gatchina	NRC KI	PIK
56	Russia	Dimitrovgrad	RIAR	RBT-10/2
57	Russia	Dimitrovgrad	RIAR	RBT-6
58	Russia	Dimitrovgrad	RIAR	SM-3
59	Russia	Dimitrovgrad	RIAR	SM-3 CA
60	Russia	Nizhniy Novgorod	OKBM	ST-1125
61	Russia	Nizhniy Novgorod	OKBM	ST-659
62	Russia	Gatchina	NRC KI	WWR-M
63	Russia	Obninsk	Karpov Institute	WWR-Ts
64	Syria	Damascus	Dar al-Hajar Nuclear Research Center	SRR-1 (MNSR)
65	United States	Idaho Falls, ID	INL	ATR
66	United States	Idaho Falls, ID	INL	ATR-C
67	United States	Pleasanton, CA	GE Vallecitos	GE-NTR
68	United States	Oak Ridge, TN	ORNL	HFIR
69	United States	Cambridge, MA	MIT	MITR-II
70	United States	Columbia, MO	University of Missouri	MURR
71	United States	Gaithersburg, MD	NIST	NBSR
72	United States	Idaho Falls, ID	INL	TREAT

SOURCE: See text in Appendix E.

LIST OF ACRONYMS FOR TABLE E.2

AERI	Atomic Energy Research Institute
CA	Critical assembly
CEA	Commissariat à l'Energie Atomique et aux Energies Alternatives
CEFR	China Experimental Fast Reactor
CERT	Centre for Energy Research and Training
CIAE	China Institute of Atomic Energy
DPRK	Democratic People's Republic of Korea
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
FCA	Fast critical assembly

Nominal P, kW	Reactor Type	Notes	IAEA #
	Critical Assembly	Research on space propulsion	RU-0081
300	Steady State		RU-0002
100,000	Steady State	Being commissioned, Designed for 100MW, Currently licensed for 100 W	RU-0016
10,000	Steady State	Uses spent fuel from SM-3	RU-0021
6,000	Steady State	Uses spent fuel from SM-3	RU-0022
100,000	Steady State	Typically operated at 90,000 kW	RU-0024
	Critical Assembly		RU-0083
	Critical Assembly		RU-0097
	Critical Assembly		RU-0094
18,000	Steady State	Also called VVR-M	RU-0008
15,000	Steady State	Also called VVR-Ts	RU-0019
27	Steady State		SY-0001
250,000	Steady State	Typically operated at 110,000-160,00 kW	US-0070
	Critical Assembly		US-0071
100	Steady State		US-0052
100,000	Steady State	Operation currently limited to 85,000 kW	US-0137
6,000	Steady State		US-0120
10,000	Steady State		US-0204
20,000	Steady State		US-0126
	Pulsed Reactor	Expected to restart by 2018	US-0018

GE	General Electric
ICENS	International Centre for Environmental and Nuclear Sciences
IGR	[name of a reactor]
ILL	Institut Laue-Langevin (Grenoble)
INL	Idaho National Laboratory
INP	Institute of Nuclear Physics
IPPE	Institute of Physics and Power Engineering
IRM	Institute of Reactor Materials
IRT	In-Reactor Thimble (Fast Test Reactor)
ITEP	Institute for Theoretical and Experimental Physics
IVG.1M	[name of a reactor]

continued

TABLE E.2 Continued

JAEA	Japan Atomic Energy Agency
KURRI	Kyoto University Research Reactor Institute
MEPhI	Moscow Engineering Physics Institute
MIT	Massachusetts Institute of Technology
MNSR-IAE	Miniature Neutron Source Reactor–Institute of Atomic Energy
MNSR-SZ	Miniature Neutron Source Reactor–Shenzhen University
NIIP	Scientific Research Institute for Instruments
NIRR	Nigeria Research Reactor
NIST	National Institute of Standards and Technology
NNC-IAE	National Nuclear Center–Institute of Atomic Energy
NRC KI	National Research Centre "Kurchatov Institute"
OKBM	[full name: "I.I. Afrikantov OKB Mechanical Engineering"]
ORNL	Oak Ridge National Laboratory
PARR	Pakistan Atomic Research Reactor
PINSTECH	Pakistan Institute of Nuclear Science and Technology
RHF	Réacteur à Haut Flux (Grenoble)
RIAR	Research Institute of Atomic Reactors
SCK·CEN	Studiecentrum voor Kernenergie·Centre d'Etudes Nucléaire
TPU	Tomsk Polytechnic University
TUM	Technische Universität München
UTR-KINKI	Kinki University Reactor
UWI	University of West Indies
WWR-K	[name of a reactor]

AGENDA

Meeting on "Updating and Optimizing a List of Civilian Research and Test Reactors That Operate Using HEU Fuel"

Vienna, Austria
27–29 July, 2015
Vienna International Center (VIC), Meeting Room MOE100

Monday, 27 July

08:30 – 09:00	Arrival at VIC
09:00 – 09:20	Opening
09:20 – 09:25	Introduction of Participants
09:25 – 09:45	Discussion and Ground Rules for Handling of Sensitive Information
09:45 – 10:30	Purpose & Scope of Meeting Presentation by National Academies and IAEA
10:30 – 11:45	Presentations:
IAEA	"IAEA Research Reactor Data Base (RRDB) Information on HEU Research Reactors and Critical Facilities" (30 minutes + 5 minutes of discussion)
United States	"Status of U.S. HEU Facilities and DOE/NNSA Conversion Activities" (30 minutes + 5 minutes of discussion)
11:45 – 13:00	*Lunch*
13:00 – 14:30	Presentations:
Russia	"Status of Russian HEU Facilities" (1 hour including discussion)
France	"Status of French HEU Facilities" (30 minutes)
14:30 – 15:00	*Coffee Break*

15:00 – 15:45 Presentations:
United Kingdom: "Status of UK HEU Facilities" (15 minutes)
Other countries: "Civilian Reactor Facilities That Operate Using HEU Fuel" (30 minutes)

15:45 – 16:00 Summary and Adjourn

Tuesday, 28 July

09:00 – 12:00 General Discussion on Combining the Lists and Identifying Discrepancies (discussion guided by location)

- North America
- South America
- Europe
- Africa
- Russia
- Asia

For each location, discussions will start with research reactors and then move to additional civilian HEU facilities (critical assemblies, subcritical assemblies, etc.). There will be a package and presentation to guide discussion.

12:00 – 13:15 *Lunch*

13:15 – 14:45 Resolve Disputed HEU Facilities

14:45 – 15:15 *Coffee Break*

15:15 – 17:30 Revise/Draft Final List

Wednesday, 29 July

09:00 – 10:30 Final Review of List and Discussion on Any Remaining Items

10:30 – 12:00 Next Steps and Closure of the Meeting

PARTICIPANT LIST

Last Name	First Name
Adelfang	Pablo
Arkhangelsky	Nikolay
Chamberlin	Jeffrey
Dix	Joan
Glaser	Alexander
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Heimberg	Jennifer
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Lemoine	Patrick
Marshall	Frances
Matos	Jim
Phillips	Julia
Podvig	Pavel
Ridikas	Danas
Roglans	Jordi
Thro	Pierre-Yves
Voronov	M.
Waud	Brian

Appendix F

HEU-Fueled Reactors Outside the Scope of the Study

As part of the effort to identify the civilian reactors operating on highly enriched uranium (HEU) fuel listed in Table 2.2, the committee also collected information on operational reactors that are considered outside the scope of this study (Arkhangelsky et al., 2012; Chamberlin, 2015; IAEA, 2000). This appendix lists reactors that are out of scope in Tables F.1 and F.2 including 30 defense-oriented (research) reactors and 9 civilian propulsion reactors. These lists may not be complete and should be considered noncomprehensive because publicly available information may be incomplete or out of date (e.g., with regard to the operational status of particular facilities).

The 2009 Academies study (NRC, 2009, p. 162) recommended that:

> DOE-NNSA [Department of Energy–National Nuclear Security Administration], in cooperation with IAEA [International Atomic Energy Agency], make an effort to maintain an up-to-date and comprehensive database of the research and test reactors of the world, including . . . reactors with a defense-oriented mission, [but not including (military) naval propulsion reactors]. . . . these reactors should be investigated to determine if it is feasible to convert them to LEU [low enriched uranium]; if so, they should become in-scope for the [GTRI (Global Threat Reduction Initiative), now M^3 (Material Management and Minimization)] program.

TABLE F.1 Operational Defense-Oriented (military) Reactors Using HEU Fuels

IAEA ID[a]	Country	Name	Power (MW)	Reactor Type	Date of Criticality
GB-0011	United Kingdom	VIPER	0	PR	1967
RU-0032	Russia	BARS-5	0	PR	1986
RU-0033	Russia	IGRIK	0	PR	1975
RU-0034	Russia	YAGUAR	0	PR	1988
RU-0035	Russia	EBR-L (= FBR-L)	0	PR	1981
RU-0052	Russia	BIGR	0	PR	1977
RU-0054	Russia	BR-1M	0	PR	1979
RU-0063	Russia	BR-K1	0	PR	1995
RU-0084	Russia	VIR-2M	0	PR	1980
RU-0103	Russia	GIR-2	0	PR	1993
RU-0104	Russia	IKAR-S	0	CA	2004
RU-0105	Russia	FKBN-2M	0	CA	1997
RU-0106	Russia	FKBN-2	0	CA	2000
	Russia	KV-1		NV	1975
	Russia	KV-2		NV	1995
	Russia	Ruslan[b]	~ 800	DUAL	1979
	Russia	Lyudmila (LF-2)[b]	~ 800	DUAL	1983
	Russia	FKBN-I	0	CA	
	Russia	Priz (=Impulse-1)		PR	
US-0106	United States	Godiva (IV)	0	CA	1951
US-0107	United States	Flattop	0	CA	1958
US-0108	United States	Comet	0	CA	1952
US-0167	United States	ACRR	4	SS	1967
US-0228	United States	Planet	0	CA	1984
US-0238	United States	S8G Prototype		NV	1978
US-0242	United States	MARF		SS	1976
US-0245	United States	Fast Burst (FBR)	0	PR	1964
	United States	MTS-626		NV	1993
	United States	MTS-635		NV	1989
	United States	TACS	0	CA	

[a] The column labeled "IAEA ID" shows the IAEA's Research Reactor Database (RRDB) numbering, if it exists for a listed reactor. If an IAEA ID is not known, then the cell is blank.
[b] Two dual-use reactors, Ruslan and Lyudmila (LF-2), are tritium production reactors that produce isotopes for the civilian market.

NOTE: Key to acronyms in table for "Type" of reactor: CA = critical assembly; NV = naval reactor; PR = pulsed reactor; SS = steady-state; DUAL = both military and civilian use; and IB = icebreaker.

SOURCE: IAEA (2000); Arkhangelsky et al. (2012); IPFM (2013); Chamberlin (2015).

TABLE F.2 Operational Civilian Propulsion Reactors Using HEU Fuels

IAEA ID[a]	Country	Name	Power (MW)	Reactor Type	Date of Criticality
	Russia	SEVMORPUT	135	IB/TS	1988
	Russia	TAYMYR	170	IB	1989
	Russia	SOVETSKIY SOYUZ-1	170	IB	1990
	Russia	SOVETSKIY SOYUZ-2	170	IB	1990
	Russia	VAYGACH	170	IB	1990
	Russia	YAMAL-1	170	IB	1993
	Russia	YAMAL-2	170	IB	1993
	Russia	50 LET POBEDY-1	170	IB	2007
	Russia	50 LET POBEDY-2	170	IB	2007

[a] The column labeled "IAEA ID" shows the IAEA's Research Reactor Database (RRDB) numbering, if it exists for a listed reactor. If an IAEA ID is not known, then the cell is blank.
NOTES: Key to acronyms in table for "Type" of reactor: IB = icebreaker, TS = transport ship.
SOURCE: IAEA (2000); Arkhangelsky et al. (2012); IPFM (2013); Chamberlin (2015).

Appendix G

Glossary

Burnable poisons: Materials that absorb excess neutrons so that criticality of the reactor is more easily maintained. Over time, these poisons are "burned" (i.e., after neutron capture, they are turned into other isotopes that absorb fewer neutrons). Ideally, as the fuel approaches its end of life, the burnable poison is fully depleted.

Conversion: The process of changing the fuel used to power a nuclear reactor. In the context of this report, the new fuel is expected to be less enriched in uranium-235 (^{235}U) than the current fuel. The fuel is preferably enriched to less than 20 percent (low enriched uranium [LEU]). This involves establishing that a reactor can operate safely on the new fuel and may also involve modifications to the reactor design and operating parameters in order to accommodate the new fuel.

Critical mass: The smallest mass of a fissionable material (e.g., ^{235}U) that will sustain a nuclear chain reaction at a constant level. http://www.thefreedictionary.com/Critical+mass+%28nuclear%29.

Dispersion fuel: Fuel for research reactors whose uranium is contained in particles dispersed in a metallic matrix, which is then enclosed within metal cladding to contain the radioactive decay products and prevent chemical reactions. Research reactor fuels used today are all of this type.

Downblending: In the context of this report, a process involving diluting HEU with LEU or other materials to give a material that is less usable (or unusable) in nuclear weapons but can still be used in research reactors.

End-of-life analysis: In the context of this report, analysis of when a research reactor will no longer be technically or economically feasible to operate. Factors influencing when the end of life occurs include the integrity of various reactor components that cannot be replaced, such as the pressure vessel, as well as the ability of the reactor to continue to be certified as safe to operate and to be licensed by the relevant regulatory bodies.

Fissile material: An atom whose nucleus is capable of undergoing fission, or splitting into two smaller nuclei, after capturing low-energy neutrons. http://www.nrc.gov/reading-rm/basic-ref/glossary/fissile-material.html.

Fuel element: A rod, tube, plate, or other geometrical form into which nuclear fuel is fabricated for use in a reactor.

NOTE: As a reactor is converted from HEU to LEU, it is important to keep the overall size and geometry of the fuel elements constant. http://encyclopedia2.thefreedictionary.com/Fuel+element.

For U.S. reactors, the term *fuel element* refers to a collection of fuel plates that are grouped together to form a single unit. For Russian reactors, the term *fuel element* refers to the fuel plates or tubes. To avoid confusion, the text uses the terms *fuel assembly* to describe a collection of *fuel plates*.

High-density LEU fuel: Reactor fuel that contains LEU that has sufficient uranium density to enable operation of high performance research reactors without significant degradation in performance. In practice, that means fuel with a uranium density exceeding about 8 gU/cm^3.

Highly enriched uranium (HEU): Uranium enriched to 20 percent or above in ^{235}U. http://www.nrc.gov/reading-rm/basic-ref/glossary/highly-or-high-enriched-uranium.html.

High performance research reactor (HPRR): Research reactors that are characterized by high neutron flux, operating power above 10 MW, and compact cores.

Hot isostatic pressing: A manufacturing process used to reduce the porosity of metals and increase the density of many ceramic materials. The process subjects a component to both elevated temperature and isostatic gas pressure in a high-pressure containment vessel. An inert gas is used to

avoid chemical reactions. Pressure is applied to the material from all directions (hence, the term *isostatic*). http://dictionary.sensagent.com/hot%20isostatic%20pressing/en-en/.

Low enriched uranium (LEU): Uranium enriched to less than 20 percent ^{235}U.

Monolithic fuel: Fuel for research reactors whose uranium is contained in a dense, uniform alloy enclosed within metal cladding to contain the radioactive decay products and prevent chemical reactions. It is possible to get much higher uranium density in the fuel using monolithic fuel rather than the more common dispersion fuel.

Neutron flux: The number of neutrons per area delivered in a given time. In this report, neutron flux values are given in neutrons per square centimeter per second.

Post-irradiation examination: The study of irradiated materials such as nuclear fuel to ascertain the effect of the radiation on the material structure and integrity. Such examination is important in the qualification of new types of reactor fuel in that it helps establish the limits of the fuel and can lead to understanding of failure modes. Such evaluation must be carried out in a hot cell to contain the radioactivity of the samples.

Reactor cycle length: The length of time a reactor can operate without refueling. In some reactors, fuel elements are moved from one position in the reactor to another between cycles, while other fuel elements are replaced with fresh ones. In other reactors, all fuel elements are replaced at the end of each cycle.

Reactor Type:

- **Subcritical assembly:** A subcritical mass of fissile material that does not have the ability to sustain a fission chain reaction. A population of neutrons introduced to a subcritical assembly will exponentially decrease.
- **Critical assembly:** An assembly of fissile material brought together in such a way that each fission event causes, on average, exactly one additional such event in a continual chain.
- **Steady state:** A reactor that can operate stably at a given power level for a long period of time by maintaining a balance between the quantity of neutrons available to induce fission events (through the presence of neutron absorbers) and the amount of fissile material.

Research reactor—from 10 CFR § 170.3: Research reactor means a nuclear reactor licensed by the Nuclear Regulatory Commission under the authority of subsection 104c of the [Atomic Energy] Act and pursuant to the provisions of § 50.21(c) of this chapter for operation at a thermal power level of 10 MW or less, and which is not a testing facility as defined in this section.

Separative work unit (SWU): The standard measure of the effort required to separate isotopes of uranium (^{235}U and ^{238}U) during an enrichment process in nuclear facilities; 1 SWU is equivalent to 1 kg of separative work.

Spallation: High-energy nuclear reaction in which a target nucleus struck by an incident particle of energy greater than about 50 million electron volts ejects numerous lighter particles such as neutrons.

Supercritical: Pertaining to a mass of radioactive material in which the rate of a chain reaction increases with time. http://dictionary.reference.com/browse/supercritical.

Test reactor—from 10 CFR 50.2: Testing facility means a nuclear reactor that is of a type described in § 50.21(c) of this part and for which an application has been filed for a license authorizing operation at:

(1) A thermal power level in excess of 10 megawatts; or
(2) A thermal power level in excess of 1 megawatt, if the reactor is to contain:
    (i) A circulating loop through the core in which the applicant proposes to conduct fuel experiments; or
    (ii) A liquid fuel loading; or
    (iii) An experimental facility in the core in excess of 16 square inches in cross-section.

Transmutation: A phenomenon that occurs when a neutron bombarding an atomic nucleus is absorbed, changing it into a different isotope of the same element or causing the nucleus to split into multiple (usually two) different elements.