United States Government Accountability Office

GAO

Report to Congressional Requesters

October 2011

NUCLEAR FUEL CYCLE OPTIONS

DOE Needs to Enhance Planning for Technology Assessment and Collaboration with Industry and Other Countries

U.S. Government Accountability Office GAO 90 YEARS 1921-2011 ACCOUNTABILITY ★ INTEGRITY ★ RELIABILITY

GAO-12-70

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Highlights

Highlights of GAO-12-70, a report to congressional requesters

October 2011

NUCLEAR FUEL CYCLE OPTIONS

DOE Needs to Enhance Planning for Technology Assessment and Collaboration with Industry and Other Countries

Why GAO Did This Study

More demand for electricity and concerns about greenhouse gas emissions have increased interest in nuclear power, which does not rely on fossil fuels. However, concerns remain about the radioactive spent fuel that nuclear reactors generate. The Department of Energy (DOE) issued a research and development (R&D) plan to select nuclear fuel cycles and technologies, some of which reprocess spent fuel and recycle some nuclear material, such as plutonium. These fuel cycles may help reduce the generation of spent fuel and risks of nuclear proliferation and terrorism. GAO was asked to review (1) DOE's approach to selecting nuclear fuel cycles and technologies, (2) DOE's efforts to reduce proliferation and terrorism risks, and (3) selected countries' experiences in reprocessing and recycling spent fuel. GAO reviewed DOE's plan and met with officials from DOE, the nuclear industry, and France and the United Kingdom.

What GAO Recommends

GAO recommends that DOE revise its plan to include the current readiness levels of fuel cycle technologies and the estimated time and cost to develop them, include a strategy for long-term collaboration with the nuclear industry, and specify how DOE will use international agreements to advance its efforts. GAO also recommends that DOE's Office of Nuclear Energy and its National Nuclear Security Administration (NNSA) complete a memorandum of understanding (MOU) to avoid duplication and overlap of efforts. DOE agreed with the first three recommendations and did not rule out the future use of a MOU. GAO continues to believe that this formal collaboration mechanism is needed.

View GAO-12-70 or key components.

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What GAO Found

DOE's R&D plan relies on a systematic approach—that is, the use of scientific methods and engineering principles—to select and demonstrate nuclear fuel cycles and associated technologies. However, it does not explain the current readiness levels of the technologies associated with the fuel cycles and the estimated time and cost of further development; it also does not explain how DOE will collaborate with the nuclear industry and other countries experienced in nuclear R&D in achieving its goals. In particular:

- In 2010, DOE screened 863 previously identified nuclear fuel cycles and technologies and grouped them into 266 fuel cycles for further exploration. Independent reviewers found this screening process useful and recommended changes that DOE officials stated they would act on.
- DOE's R&D plan states that it is necessary to assess the readiness levels of technologies associated with nuclear fuel cycles. However, neither the plan nor the screening process describe the current readiness levels of all critical technologies or the time or estimated costs for further development. As GAO has reported, assessing the readiness of technology is a best practice to help control schedule and costs.
- DOE's R&D plan states the importance of collaborating with the nuclear industry—the ultimate user of any fuel cycle and technologies that are developed—and DOE continues to get industry advice. However, the plan does not include a strategy for long-term collaboration with industry, without which DOE cannot be assured that the nuclear industry will accept and use the fuel cycles and technologies that the department may develop.
- DOE has agreements with other countries that provide collaborative opportunities to share research results and leverage DOE's R&D efforts, such as using the countries' research facilities. However, the plan does not explain how DOE will use these agreements to advance its R&D goals.

As stated in DOE's R&D plan, the Office of Nuclear Energy has efforts under way to minimize proliferation and terrorism risks associated with nuclear power, but faces challenges. These challenges include developing reliable and cost-effective fuel cycles while minimizing the attractiveness to potential adversaries of radioactive materials resulting from these cycles. NNSA is also working on these issues, and the two agencies have worked together informally to avoid duplication and overlap but do not have a formal mechanism to collaborate on future efforts, which can help agencies strengthen their commitment to work collaboratively by clarifying who will lead or participate in which activities and how decisions will be made.

GAO reviewed France's and the United Kingdom's decades of experiences in developing and operating reprocessing and recycling infrastructures. These experiences can provide some insights into the decisions DOE may need to make in selecting nuclear fuel cycles and technologies. For example, reprocessing and recycling is likely to reduce the amount of space needed for a nuclear waste repository because some of the radioactive materials are reused, but the amount of this reduction would depend on how much of the radioactive materials that are reused might ultimately require disposal in such a repository.

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Abbreviations

AGR	advanced gas-cooled nuclear reactor
ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs (French National Radioactive Waste Management Agency)
CEA	Commissariat á l'Énergie Atomique (French Atomic Energy Commission)
DOE	Department of Energy
EdF	Electricité de France
GNEP	Global Nuclear Energy Partnership
HLW	high-level waste
IAEA	International Atomic Energy Agency
ID/IQ	Indefinite Delivery and Indefinite Quantity
IFNEC	International Framework for Nuclear Energy Cooperation
ILW-LL	intermediate-level waste long lived
INL	Idaho National Laboratory
LLW	low-level waste
MOX	mixed oxide
NDA	Nuclear Decommissioning Authority (United Kingdom)
NEA	Nuclear Energy Agency
NNSA	National Nuclear Security Administration
OECD	Organization for Economic Co-operation and Development
R&D	research and development
THORP	Thermal Oxide Reprocessing Plant
U.K.	United Kingdom
UP	Usine de Plutonium (Plutonium Factory)

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United States Government Accountability Office
Washington, DC 20548

October 17, 2011

The Honorable Fred Upton
Chairman
Committee on Energy and Commerce
House of Representatives

The Honorable Edward J. Markey
House of Representatives

In recent years, there has been a worldwide push to develop commercial nuclear power, propelled in part by the need to keep pace with higher demands for electricity and by concerns about greenhouse gas emissions, which result primarily from the burning of fossil fuels. As of July 2011, the United States had 104 operating nuclear power reactors, 1 under construction, and 34 planned or proposed for construction by 2030. In addition, other countries have a combined total of 336 operating reactors, 60 nuclear reactors under construction, and 463 planned or proposed for construction over the next two decades. Nuclear energy, which supplied about 20 percent of the nation's electric power in 2010, offers a domestic source of electricity with low emissions but also presents difficulties—including what to do with nuclear fuel after it has been used and removed from commercial power reactors. This material, known as spent nuclear fuel, is highly radioactive and considered one of the most hazardous materials on earth. The accident involving the nuclear reactors in Fukushima, Japan, which were damaged by the March 2011 earthquake and tsunami, once again brought to the fore concerns about the potential for nuclear reactors to fail and problems in dealing with the spent nuclear fuel generated by these reactors.

Nuclear power generation depends on the nuclear fuel cycle—that is, the process of mining uranium, enriching it, fabricating it into nuclear fuel, fissioning the fuel in a nuclear reactor, and managing the spent fuel once it is removed from the reactor.[1] Once the spent nuclear fuel, which contains plutonium from the fissioning process, is removed, it may be stored for

[1]Fission is a reaction in which the nucleus of an atom splits into small parts, releasing energy. A commercial nuclear reactor uses this energy to produce electricity.

eventual disposal in a geologic repository.[2] This approach to generating nuclear energy is referred to as a once-through or open fuel cycle and is the approach U.S. nuclear utilities use. By contrast, in a closed fuel cycle, the spent nuclear fuel is reprocessed to separate the plutonium from the uranium and other radioactive materials for reuse. It may then be recycled either by mixing the plutonium with uranium from another source to make mixed oxide fuel, or MOX fuel, or by fabricating new nuclear fuel, known as reprocessed uranium fuel, by using the uranium resulting from reprocessing. Other countries, such as France, rely on a closed fuel cycle to manage their spent nuclear fuel. According to the Department of Energy (DOE), an advantage of reprocessing and recycling includes the greater use of the energy content of the original fuel and a reduction in the amount of radioactive waste requiring disposal in a geologic repository. According to a report from the National Nuclear Security Administration (NNSA)—a semi-autonomous agency within DOE with a lead role in addressing proliferation and terrorism risks—a key disadvantage of reprocessing is that it separates out plutonium in the spent nuclear fuel, which can be used in a nuclear weapon.[3] According to the same NNSA report, other nations might use this process to divert plutonium for a nuclear weapon, and terrorists might seek to steal plutonium or other material that could be used in a nuclear explosive device.

Until the mid-1970s, the United States reprocessed spent nuclear fuel but reverted to the once-through fuel cycle, primarily to discourage other countries from pursuing reprocessing because of concerns over nuclear proliferation. In 2006, DOE announced its intention to reconsider reprocessing spent nuclear fuel, as part of an effort known as the Global Nuclear Energy Partnership (GNEP). Under GNEP, DOE proposed, among other things, building multibillion-dollar nuclear facilities to demonstrate advanced reprocessing and recycling technologies that could significantly reduce waste, as well as reduce proliferation and terrorism risks by making nuclear fuel in a manner that is less useful to

[2]Since the publication of a 1957 report by the National Academy of Sciences, a geologic repository has been considered the safest and most secure method of isolating spent nuclear fuel and other types of nuclear waste from humans and the environment.

[3]NNSA, *Draft Nonproliferation Impact Assessment for the Global Nuclear Energy Partnership Programmatic Alternatives* (Washington, D.C.: December 2008).

adversaries.[4] However, in April 2008, we reported that the technologies that DOE proposed for demonstration were not sufficiently developed to warrant the building of commercial-scale facilities and that DOE's backup plan to rely on commercially available technology would not meet GNEP's goals of significantly reducing waste and minimizing proliferation risk.[5]

Congress eliminated funding for GNEP in fiscal year 2009.[6] The House Committee on Appropriations encouraged the next administration to take a more comprehensive and responsible approach to the management of spent nuclear fuel and high-level radioactive waste.[7] The Committee supported DOE's research on nuclear fuel cycles but provided no funding for the design and construction of facilities for recycling spent nuclear fuel and for associated research facilities. Instead, the Committee directed DOE to focus on reducing the waste generated by reprocessing spent nuclear fuel, designing safeguard measures for reprocessing facilities, and researching ways to reduce the proliferation risks of reprocessing spent nuclear fuel. Moreover, the Committee directed the department to continue to coordinate this research effort with other countries having advanced fuel cycle capabilities, such as France and the United Kingdom. In January 2010, in a memorandum to the Secretary of Energy, the President directed DOE to establish the Blue Ribbon Commission on America's Nuclear Future to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense spent nuclear fuel and nuclear waste. The Commission issued a draft report on July 29, 2011, and plans to issue a final report in January

[4]In 2008, GAO estimated that the cost of a commercial reprocessing plant would be approximately $44 billion to reprocess 3,000 metric tons of spent nuclear fuel annually. This estimate was developed by using DOE's guideline for scaling facilities of different sizes to extrapolate from the design of an 800 metric ton reprocessing facility built in Japan that is estimated to have cost almost $20 billion.

[5]GAO, *Global Nuclear Energy Partnership: DOE Should Reassess Its Approach to Designing and Building Spent Nuclear Fuel Recycling Facilities,* GAO-08-483 (Washington, D.C.: Apr. 22, 2008).

[6]Pub. L. No. 111-8 (2009).

[7]H.R. Rep. No. 110-921 (2008).

2012, after considering public comments.[8] The draft report discussed, among other things, the current status of nuclear fuel cycles and associated technologies and the extent to which DOE contributes to efforts to further develop them, as well as other countries' experiences in waste management programs and their potential usefulness for the United States.

In April 2010, DOE's Office of Nuclear Energy issued a new research and development (R&D) "roadmap" for nuclear energy with four objectives, followed by separate implementation plans for each of these objectives.[9] In this report, we refer to the roadmap and the implementation plans collectively as DOE's R&D plan. This report focuses on two of these objectives.[10] Under the first objective, DOE seeks to select and demonstrate sustainable nuclear fuel cycles. According to DOE, sustainable nuclear fuel cycles are those that would better utilize uranium resources, maximize energy generation, minimize waste generation, improve safety, and limit proliferation and terrorism risks. DOE acknowledges that its key challenge in this objective is to develop a suite of options that will enable future decision-makers to make informed choices about how best to manage the spent fuel from reactors. Under the second objective, DOE seeks to understand and minimize the potential risks of proliferation and terrorism associated with the technologies for reprocessing and recycling.

In this context, you asked us to review DOE's plans to assess nuclear fuel cycles and associated technologies and other countries' experiences with these technologies. Our objectives were to review the (1) approach DOE is taking to select and demonstrate nuclear fuel cycles and associated technologies, (2) efforts DOE is making to understand and minimize

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[8]Blue Ribbon Commission on America's Nuclear Future, *Draft Report to the Secretary of Energy* (Washington, D.C.: July 29, 2011). The commission includes recognized representatives and experts from a range of disciplines and with a range of perspectives, and also includes participation of appropriate federal officials.

[9]DOE, *Report to Congress: Nuclear Energy Research and Development Roadmap* (Washington, D.C.: Office of Nuclear Energy, April 2010).

[10]This report does not address the other two objectives in DOE's R&D plan, which are to (1) develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors and (2) develop improvements in the affordability of new reactors to enable nuclear energy to help meet the administration's energy security and climate change goals.

nuclear proliferation and terrorism risks associated with these nuclear fuel cycles and technologies, and (3) experiences of France and the United Kingdom in reprocessing and recycling spent nuclear fuel that may be useful to the United States in selecting fuel cycles and technologies.

To address these objectives, we reviewed DOE's approach to implement its new R&D plan for selecting and demonstrating nuclear fuel cycles and understanding and minimizing the risks of proliferation and terrorism. We obtained and reviewed pertinent documents and interviewed cognizant Office of Nuclear Energy officials, as well as officials from the NNSA and the Department of State, which are two of the federal government's lead agencies for proliferation and terrorism risks. We visited experts at the Idaho National Laboratory, which is the Office of Nuclear Energy's lead laboratory; and interviewed a nonprobability sample of experts at other national laboratories, such as the Oak Ridge National Laboratory, Brookhaven National Laboratory, and the Los Alamos National Laboratory, about nuclear fuel options, waste management, proliferation and terrorism risks, and related issues. Because we used a nonprobability sample of experts at national laboratories to speak with, the information we obtained from these experts cannot be generalized to all experts at all national laboratories, but the interviews provided us with information on the perspectives of various experts from the national laboratories. We also conducted semi-structured interviews with five subject matter experts who could provide a range of views on reprocessing and recycling spent nuclear fuel and on DOE's R&D plan. To select these experts for interviews, we reviewed presentations given by them before the Blue Ribbon Commission, reviewed literature by experts who had conducted extensive research on relevant issues, and sought recommendations from other subject matter experts and government officials. We also attended an international conference and DOE workshops on recycling technologies and reviewed pertinent documents delivered by witnesses to and issued by the Blue Ribbon Commission. In addition, we interviewed representatives from the six nuclear industry groups that signed contracts with DOE in 2010 to provide advice and information on its ongoing and planned R&D.[11] We also spoke with representatives from a nonprobability sample of two nuclear utility companies out of the 26 operating in the United States; the Nuclear Energy Institute, a policy organization for the

[11]These nuclear industry groups are AREVA, CH2M Hill, ENERCON, EnergySolutions, GE-Hitachi, and Shaw. Each of these groups includes one or more partners.

nuclear energy and technologies industry; and the Electric Power Research Institute, an independent, nonprofit organization that provides R&D relating to the generation, delivery, and use of electricity. Because we used a nonprobability sample of nuclear utility companies to speak with, the information we obtained from them cannot be generalized to all nuclear utility companies, but the interviews we had with utility company representatives provided us with information on the perspectives of nuclear utility companies.

To obtain information on the operating experiences of reprocessing and recycling spent nuclear fuel in France and the United Kingdom, we reviewed relevant documents about their nuclear power systems and visited these countries to obtain additional documents and interview government, nuclear industry, and utility representatives who oversee and manage the reprocessing and recycling infrastructures. We selected France and the United Kingdom because they are among the few countries that have decades of experience in reprocessing and recycling spent nuclear fuel. We observed the operations of facilities in these countries that reprocess spent nuclear fuel and that fabricate MOX fuel. In addition, we spoke with officials from selected international nuclear organizations: the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD-NEA), the International Atomic Energy Agency (IAEA), and the World Nuclear Association, to obtain an international perspective on reprocessing and recycling spent nuclear fuel.[12] We also interviewed selected subject matter experts in France and the United Kingdom on these countries' experiences with reprocessing and recycling.

We conducted this performance audit from May 2010 through October 2011, in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for

[12]The Nuclear Energy Agency assists member countries in maintaining and further developing the scientific, technological, and legal bases required for the safe, environmentally friendly and economical use of nuclear energy for peaceful purposes. It is part of the United Nations' Organization for Economic Cooperation and Development and is headquartered in Paris, France; IAEA works with member states and multiple partners worldwide to promote safe, secure, and peaceful nuclear technologies and is headquartered in Vienna, Austria; and the World Nuclear Association, headquartered in London, England, is a nuclear industry organization that promotes commercial nuclear power.

our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives. Appendix I describes our scope and methodology in more detail.

Background

This section discusses (1) nuclear fuel assemblies and their use, (2) the composition of spent nuclear fuel, (3) nuclear fuel cycles, (4) goals to minimize the risks of nuclear proliferation and terrorism, and (5) technology readiness assessments to measure and communicate the risks of using technology in first-of-a-kind applications.

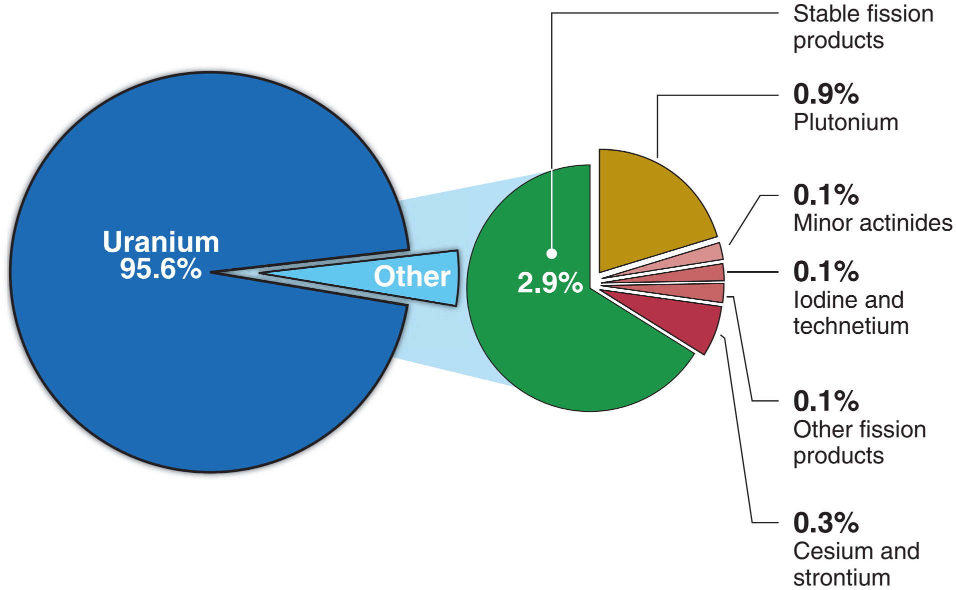
Nuclear Fuel Assemblies and Their Use

Hundreds of nuclear fuel assemblies—bundles of long metal tubes filled with enriched uranium fuel pellets—form the core of a typical nuclear power reactor. Reactors produce energy when uranium atoms split (fission) into smaller elements, called fission products. Some of the uranium atoms do not split but rather transmute into elements with atomic weights heavier than uranium, such as neptunium, plutonium, americium, and curium. With the buildup of fission products in the enriched uranium, the fuel loses its ability to sustain a nuclear reaction, and the fuel assemblies are then replaced with new fuel. Removed assemblies contain spent nuclear fuel, the radiation from which, without protective shielding, can kill a person directly exposed to it within minutes or increase the risk of cancer in people exposed to smaller doses.

Composition of Spent Nuclear Fuel

Figure 1 shows the composition of spent nuclear fuel.

Figure 1: Composition of Spent Nuclear Fuel



Source: GAO analysis of DOE data.

Spent nuclear fuel includes only the fuel components and not the assemblies used to contain these components. As shown in the figure, the fuel components of the spent fuel are uranium, plutonium, minor actinides, and fission products. Minor actinides are a group of transuranic by-products produced in nuclear reactor operation that are major contributors to the long-lived hazards of radioactive waste. The term transuranic generally applies to radioactive material containing radionuclides (radioactive elements) with atomic numbers higher than 92 (uranium's atomic number) and half-lives longer than 20 years in concentrations exceeding 100 nanocuries (a measure of radioactivity) per gram. Some fission products, such as cesium, strontium, iodine, technetium, and other fission products are radioactive and can remain dangerous for hundreds to hundreds of thousands or millions of years. Stable fission products do not emit radiation.

As the figure shows, uranium is the primary component in spent nuclear fuel. Uranium and plutonium are part of a group of elements known as actinides—the 15 chemical elements on the periodic table with atomic numbers from 89 to 103, actinium through lawrencium—and are also called major actinides. Major actinides are fissile—they easily undergo fission when hit by a neutron of any energy.[13] Minor actinides consist primarily of neptunium, americium, and curium. Unlike major actinides, minor actinides can be made to fission only when hit by a neutron with high enough energy. Both major and minor actinides pose health and environmental risks, some for hundreds of thousands of years. The remaining component of the material in spent nuclear fuel is fission products, primarily cesium, strontium, iodine, and technetium; and stable fission products. Some fission products, such as cesium and strontium, pose environmental risks for hundreds of years after being removed from a reactor, while iodine and technetium can remain hazardous for hundreds of thousands or millions of years. Other fission products are stable and no longer emit radiation.

Nuclear Fuel Cycles

The term "fuel cycle" may either denote the general process of preparing, fissioning, and disposing of spent nuclear fuel or one of potentially hundreds of specific processes and combinations of technologies that may be used to carry out this process. The details of a specific fuel cycle include the type of fuel, the level of uranium enrichment, the type of nuclear reactor, and the methods for reprocessing, recycling, and/or disposing of spent fuel. After a period of operation, usually every 18 months, U.S. nuclear reactors generally replace some of their fuel and store the spent fuel immersed in pools of water or move them into dry storage containers.

As we recently reported, the current nuclear fuel cycle used in most U.S. reactors presents several challenges, including the lack of a geologic repository for permanent disposal of spent nuclear fuel.[14] DOE is proposing to select and demonstrate sustainable nuclear fuel cycles that could address this and other challenges. DOE's R&D plan defined sustainable fuel cycles as those that would better utilize uranium resources, maximize energy generation, minimize waste generation,

[13]A neutron is a subatomic particle with no electric charge.

[14]GAO, *Nuclear Waste: Disposal Challenges and Lessons Learned from Yucca Mountain*, GAO-11-731T (Washington, D.C.: June 1, 2011); *DOE Nuclear Waste: Better Information Needed on Waste Storage at DOE Sites as a Result of Yucca Mountain Shutdown*, GAO-11-230 (Washington, D.C.: Mar. 23, 2011); and *Commercial Nuclear Waste: Effects of a Termination of the Yucca Mountain Repository Program and Lessons Learned*, GAO-11-229 (Washington, D.C.: Apr. 8, 2011).

improve safety, and limit proliferation and terrorism risks. To achieve this objective, DOE proposes R&D on technologies for three categories of fuel cycles:

- *Once-through fuel cycle*—technologies to more efficiently use uranium than the current open fuel cycle while reducing the amount of radioactive waste generated.
- *Modified open fuel cycle*—technologies that more efficiently use uranium, minimize the amount of radioactive waste generated, and reduce proliferation and terrorism risks using limited or no reprocessing or recycling.
- *Full recycle fuel cycle*—technologies to repeatedly reprocess and recycle nuclear fuels, thereby minimizing the amount of radioactive waste generated and reducing proliferation and terrorism risks.

Goals to Minimize Risks of Nuclear Proliferation and Terrorism

According to DOE's R&D plan, it is important to ensure that the benefits of nuclear power can be obtained in a manner that limits nuclear proliferation and terrorism risks. The plan states that the Office of Nuclear Energy is responsible for providing technical expertise and leadership on nuclear technology to the federal agencies with overall responsibility for U.S. nuclear nonproliferation policy. These agencies include NNSA, as well as the Department of State, and the Nuclear Regulatory Commission—responsible for overseeing the nation's 104 commercial nuclear reactors—and other organizations. According to an NNSA official, the goals of U.S. nuclear nonproliferation policy are to:

- limit the spread of technologies to enrich uranium and to reprocess spent nuclear fuel;
- strengthen the international safeguards system, which includes international agreements to protect against misuse of nuclear technologies and international design standards for nuclear facilities;
- halt the build-up, and eventually draw down, of stocks of separated plutonium; and
- develop nuclear fuel cycles and associated technologies that have lower proliferation and terrorism risks, while recognizing that other factors contribute to proliferation and terrorism risks, such as the country in which a nuclear facility is located.

In pursuing these goals, NNSA distinguishes between nuclear proliferation and terrorism risks. According to a national laboratory subject matter expert, assessment of proliferation risks considers whether nations that have nuclear facilities for peaceful purposes, such as nuclear power, might divert and misuse these facilities to generate material to build nuclear weapons. International safeguards under the auspices of the IAEA are used to guard against these risks. Generally, because of the technology involved, NNSA considers that proliferation risks will occur over an extended period of time. In contrast, terrorism risks come from groups not necessarily associated with a particular nation. Threats associated with terrorism include the theft of nuclear material and the sabotage of nuclear facilities.

Technology Readiness Assessments

As we previously reported, technology readiness assessment provides a systematic way to determine the extent to which a technology critical to ensuring a project's successful operation is sufficiently developed for its intended purpose.[15] Critical technologies are those that are essential to a project's success and are either new or are being applied in a new manner. DOE has begun to assess the readiness of technologies for recycling spent nuclear fuel using technology readiness levels, a method pioneered by the National Aeronautics and Space Administration for measuring and communicating the risks associated with critical technologies in first-of-a-kind applications. Using a scale from one (basic principles observed) through nine (total system used successfully in project operations), readiness levels show the extent to which technologies have been demonstrated to work as intended. A higher readiness level indicates a new technology has better demonstrated its suitability relative to a specific set of criteria, and a decision to proceed with an acquisition of the technology will accordingly be lower risk. Demonstration of new technologies at successively larger scales—laboratory scale, engineering/pilot scale and full/prototypical scale—is one way to increase their technology readiness, thereby mitigating the risk of schedule or cost overruns in the design and construction of commercial-scale facilities and limiting investment in potentially ineffective technologies. As we have previously reported, GAO considers level seven (subsystem demonstrated in an operational environment) to be an

[15] GAO, *Department of Energy: Major Construction Projects Need a Consistent Approach for Assessing Technology Readiness to Help Avoid Cost Increases and Delays*, GAO-07-336 (Washington, D.C.: Mar. 27, 2007).

acceptable level of readiness before proceeding with final design and committing to definitive schedule and cost estimates.[16]

DOE's R&D Plan Lays Out a Systematic Approach to Selecting and Demonstrating Nuclear Fuel Cycles but Lacks Important Details

DOE's R&D plan details a systematic approach—that is, the use of scientific methods and engineering principles—to select and eventually demonstrate nuclear fuel cycles and associated technologies. However, the plan does not explain the current readiness of the critical technologies and the estimated time and costs of further developing these technologies; it also does not explain how DOE will collaborate with the nuclear industry and other countries with experience in conducting nuclear R&D in achieving its goals.

DOE's R&D Plan Relies on a Systematic Approach to Selecting Nuclear Fuel Cycles and Their Technologies for Further R&D

DOE's plan lays out R&D objectives for various technical areas and schedules for achieving them. Under the plan, DOE has the goal of selecting nuclear fuel cycle options and associated technologies by 2020 and demonstrating them by 2050. Throughout this selection process, the plan states that DOE will rely on a science-based approach in conducting its R&D. This approach will involve small-scale experiments, theory development, and computer modeling and simulation. The plan states that DOE will develop theories and use the knowledge and data obtained through experiments to, among other things, develop and validate modeling and simulation tools to examine nuclear fuel cycles and associated technologies.

DOE is also following a dual-path approach for nuclear fuel cycle R&D—simultaneously pursuing evolutionary and revolutionary tracks across all of its technical R&D areas. That is, according to DOE's R&D plan, the department is pursuing both advancements of existing fuel cycles and high-risk, high-payoff technologies that, if successful, could replace all or part of the evolutionary technologies. For example, DOE is pursuing a way to economically extract uranium from seawater, which it would consider a revolutionary breakthrough nuclear fuel cycle option, if it were to succeed.

[16] GAO-07-336.

To integrate its R&D efforts to select sustainable nuclear fuel cycles, DOE is relying on a systems engineering approach. According to DOE's systems engineering guide, a systems engineering approach is an approach that supports management in clearly defining the mission or problem; managing system functions and requirements; identifying and managing risk; establishing bases for informed decision-making; and verifying that products and services meet customer needs.[17]

DOE's plan for developing a sustainable nuclear fuel cycle over the next 4 decades is divided into the following eight technical R&D areas:

- *Systems analysis.* Development of computer modeling and simulation to improve understanding of the interdependences between nuclear fuel cycle subsystems and associated technologies.

- *Fuel resources.* Research to better understand the availability of uranium and other nuclear fuel materials to help inform decisions on choosing nuclear fuel cycles.

- *Fuel development*. Research to examine a wide variety of nuclear fuel to support multiple nuclear fuel cycle options.

- *Separations.* Development of new separations methods (i.e., reprocessing) that enable the recycling and/or transmutation of key nuclear fuel constituents. These methods must be economical (i.e., involve minimal processing), minimize waste streams and volumes, and enable effective safeguarding of fissile material.

- *Waste forms.* Development of new technologies for mixing high-level radioactive waste with different materials, such as ceramics, glasses, glass-ceramics, and metals to derive a waste form that can maintain stability and durability under long-term exposure to high levels of radiation, among other things, and to understand the performance of these waste forms in complex geologic settings.

- *Storage and disposal.* Research to identify alternatives to current practices and the development of technologies to enable the storage,

[17]DOE, *Managing Design and Construction Using Systems Engineering for Use with DOE O 413.3A* (Washington, D.C.: Sept. 23, 2008).

transportation, and disposal of spent nuclear fuel and wastes generated by existing and future nuclear fuel cycles.

- *Transmutation technology.* Development of systems, including nuclear reactors, that would transmute radioactive materials recovered from spent fuel to improve the use of the nuclear fuel and significantly reduce the radioactivity associated with these materials.
- *Materials, protection, control, and accountability technology.* The development of new processes and technologies to account for and protect nuclear materials from proliferation and terrorism risks.

In addition to these technical R&D areas, in 2010, DOE began to evaluate fuel cycle options in order to guide its R&D program. DOE's R&D plan defines the following eight criteria to be used in evaluating the desirability of sustainable nuclear fuel cycle options:

- *Nuclear waste management.* The weight and volume of the hazardous material generated from a nuclear fuel cycle and the implications of these factors on disposition of the waste.
- *Resources.* The effect of a nuclear fuel cycle on the availability of nuclear fuel resources over the long term, and the disposal needs associated with the fuel cycle approach that must be considered in light of the expected availability of disposal sites.
- *Proliferation risks.* How the following three factors associated with a nuclear fuel cycle could determine the overall proliferation and terrorism risks of that cycle: the extent to which (1) the cycle generates material that could be easily handled, (2) technologies are used that could produce weapons-usable material, such as uranium enrichment and reprocessing technologies, and (3) enrichment and reprocessing could be protected from misuse.
- *Safety.* Difficulty of developing fuel cycles that are capable of obtaining approval from the Nuclear Regulatory Commission for safe operations and for the disposal of radioactive waste from a nuclear fuel cycle.
- *Security.* Whether physical security for a nuclear fuel cycle can be provided that could prevent terrorists or others from gaining access to the material.

- *Economics.* The life-cycle costs of a nuclear fuel cycle, including costs for designing, constructing, operating, dismantling, and disposing of nuclear facilities and associated wastes.

- *Environmental impact.* The environmental impacts of a nuclear fuel cycle, including the impacts from constructing, operating, dismantling, and disposing of nuclear facilities and associated wastes.

- *Technology readiness.* The time needed and the cost of developing the technologies associated with a nuclear fuel cycle.

In 2010, DOE initiated a pilot screening process to systematically evaluate nuclear fuel cycle options and associated technologies for each of the three categories of fuel cycles to help guide long-term R&D. This process used systems engineering principles to develop and demonstrate a methodology for comparing alternative nuclear fuel cycles with the once-through cycle using the eight criteria above. In August 2010, DOE held two workshops to seek input from representatives of the nuclear industry and subject matter experts on this methodology.

After reaching consensus from workshop participants on a revised set of evaluation criteria and metrics for the proposed methodology, DOE convened a panel of national laboratory experts to apply it, starting with a list of 863 nuclear fuel cycle options and their associated technologies resulting from prior DOE R&D efforts. As reported to DOE, the laboratory experts revised this list by categorizing options according to key characteristics—such as the number and type of reactors used, the fuel type, and the need for reprocessing. By consolidating options that were similar, the experts ultimately produced a list of 266 nuclear fuel cycle options and associated technologies: 100 were associated with the once-through cycle, 60 with the modified open cycle, and 106 with the full recycling fuel cycle category. The laboratory experts then weighted a subset of DOE's evaluation criteria to determine which options were the most promising for developing sustainable nuclear fuel cycles, which had modest potential, and which would provide only minor benefit and thus would be considered not worth long-term R&D investments. Table 1 shows the results of this analysis. As the table shows, 83 of 103, or 81 percent, of the most promising options fell under the full recycle category and 24 of 50, or 48 percent, of the options with only a minor benefit fell under the modified open fuel cycle category. The experts noted that these findings can be helpful in focusing DOE's R&D efforts.

Table 1: Potential Promise of Options for Developing a Sustainable Nuclear Fuel Cycle

Fuel cycle	Most promising	Modest potential	Minor benefit	Total
Once through	20	54	26	**100**
Modified open	0	36	24	**60**
Full recycle	83	23	0	**106**
Total	**103**	**113**	**50**	**266**

Source: GAO analysis of DOE data.

In January 2011, the screening process methodology and results were peer reviewed by an independent panel of four national laboratory experts and two consultants. According to the panel, the screening process and its conclusions were "reasonable and useful for a pilot project" and the results will help inform DOE on what R&D efforts should be dropped and others that should continue irrespective of shifts in policy. However, this panel also found that the proposed methodology had many inherent limitations, such as a lack of nonproliferation criteria and performance metrics, and suggested specific areas for improvement. Suggested improvements included using experts independent of the national laboratories to determine if the results can be replicated; developing metrics that consider the effects of the entire fuel cycle, such as mining, uranium enrichment, and nuclear waste disposal; and further developing metrics for technology readiness and proliferation and terrorism risks.

In June 2011, the Nuclear Energy Advisory Committee, a group of experts established to provide independent advice to DOE, provided comments on its review of the pilot screening process. The committee noted that some of the evaluation criteria, such as proliferation risk, are not appropriate for advanced systems and innovative technologies that are not close to deployment and not well understood. As such, the committee suggested caution in applying the evaluation criteria at the early stages of development to avoid prematurely ruling out some fuel cycle options and their associated technologies for further R&D. The committee also stated that because the pilot screening process results are affected by the weights given to the evaluation criteria, and the determination of these weights is more a policy issue than a technical issue, DOE needs to be involved in setting the relative weights for each evaluation criteria. In addition, the committee suggested that DOE obtain the comments from the nuclear industry on the process. According to DOE officials, the office has begun to take actions to follow up on the suggestions of the peer review panel, the Nuclear Energy Advisory

Committee, and other sources in planning to conduct a formal nuclear fuel cycle screening process during fiscal year 2013.

DOE's R&D plan acknowledged that the recommendations of the Blue Ribbon Commission might affect DOE's R&D direction. In its July 2011 draft report to the Secretary of Energy, the commission found that no currently available or reasonably foreseeable reactors and fuel cycle technologies—including advances in reprocessing and recycling—have the potential to fundamentally alter the waste management challenge the United States faces over at least the next several decades. As a result, the commission concluded, it is "premature" for the United States to now commit irreversibly to a closed fuel cycle because of the large uncertainties about the merits and commercial viability of different fuel cycles and technologies. Nevertheless, the commission also concluded that the United States should continue to pursue a program of nuclear energy R&D, both to improve the safety and performance of existing nuclear energy technologies and to develop new technologies that could offer significant advantages in, among other things, safety, cost, waste management, and nonproliferation and counterterrorism.

In discussing DOE's R&D plan, the commission stated that it provides a good science-based step toward the development of an effective, long-term R&D program. It recommended that DOE update its nuclear energy R&D roadmap once every 4 years and that in doing so this process should be informed by broader strategic planning efforts, such as DOE's recently launched quadrennial technology and energy review processes.

DOE Plans to Assess Technology Readiness, but It Has Not Explained the Current Readiness of Fuel Cycle Technologies or the Estimated Time and Cost Associated with Their Development

DOE's R&D plan states that it is necessary to assess the readiness of technologies associated with the nuclear fuel cycles in selecting fuel cycle options for further review. According to the R&D plan, DOE is to assess the status of the technologies associated with the different nuclear fuel cycle options being considered and estimate the time and costs of further developing them. The plan also states that DOE will:

- continue to evaluate the technological readiness of fuel cycle options and determine the readiness of these options to differentiate among them and to focus development in order to meet the R&D plan's schedules and goals;
- give priority to R&D on technologies associated with the modified open fuel cycle because of their relative immaturity compared with the

technologies associated with once-through and full recycle fuel cycles; and

- seek to raise the readiness of the technologies associated with the modified open fuel cycle category in order to make meaningful comparisons among the three nuclear fuel cycle categories, and to further narrow the range of fuel cycle options.

These proposed actions would help advance DOE's goals for developing nuclear fuel cycle options, but neither the R&D plan nor the pilot screening process describes the current readiness of the fuel cycle options and associated technologies under consideration, the estimated time or cost for further developing them, or relate readiness to schedules and goals. As we have reported, assessing the readiness of technology is a best practice to help control schedule and costs.[18] It may be premature to assess technology readiness levels for all the fuel cycle options and associated technologies under consideration, however, without this information, DOE has not made clear the magnitude of the effort necessary to develop these technologies nor the costs associated with doing so.

DOE's R&D Plan Identifies the Need to Collaborate with the Nuclear Industry but Does Not Include a Long-term Collaboration Strategy

DOE's R&D plan identifies the importance of collaborating with the nuclear industry—the ultimate user of any nuclear fuel cycle and associated technologies that are developed—and the department has made some efforts to obtain industry advice, but the plan does not include a long-term strategy for how to conduct such collaboration. According to the R&D plan, the federal government is responsible for managing disposal of spent nuclear fuel, but the nuclear industry will be the likely user of any technologies developed by the government to better manage this fuel. Hence, the plan states that the nuclear industry is a necessary partner in DOE's R&D effort, both to suggest specific challenges to solve and to offer perspective on proposed nuclear fuel cycle options.

As of June 2011, DOE had obtained industry views by contracting with six consortia of nuclear industry companies. In December 2009, DOE issued a request for advice and assistance from companies with experience in advancing nuclear energy concepts through the licensing and deployment

[18] GAO-07-336.

of full-scale production facilities.[19] The request also stated that DOE was seeking studies, analyses, evaluations, and engineering and technical services from the nuclear industry. DOE received proposals from 14 nuclear industry groups and contracted with 6 of them in June 2010 through a 5-year, $30 million contract—known as an Indefinite Delivery and Indefinite Quantity (ID/IQ) agreement. Through the ID/IQ agreement, DOE can issue a request for information, known as a task order, from one or more of the industry groups, and each group may choose to participate or not in each task order. As of June 2011, DOE had issued five task orders, for a total of $5 million paid to the industry groups.[20] Four of the industry groups participated in the first task order by, among other things, providing input through conference calls, face-to-face meetings, attending an annual meeting, and submitting reports that identified technical areas for nuclear fuel cycle R&D efforts. The face-to-face meetings have included workshops DOE held from July 2010 through January 2011, according to DOE documents we reviewed. These workshops focused on different aspects of DOE's eight technical R&D areas. Representatives from industry groups told us that the ID/IQ agreements are an effective mechanism to solicit their input on these R&D areas in the short-term. However, some of these representatives told us that it was unclear how DOE is using the information the industry provided during workshops and in response to task orders. Moreover, DOE officials did not provide information to us on how it was using industry input.

Nevertheless, DOE's R&D plan does not include a long-term strategy for working with the nuclear industry to ensure acceptance and use the technologies DOE develops. The plan has established milestones through 2050, but its current contracts with nuclear industry partners end in May 2012, with an option to extend the contracts until May 2015. The R&D plan provides no detail on how DOE might collaborate with the nuclear industry beyond these dates. According to our analysis of the report on the pilot screening process, DOE stated that, as it continues to

[19]DOE issued a request for proposals on the U.S. General Services Administration's Federal Business Opportunities Web site in December 2009. This Web site is the single governmentwide point-of-entry for federal government procurement opportunities worth more than $25,000.

[20]The task orders included (1) support to technical campaigns, (2) technical data to justify full burn up credit in criticality safety licensing analyses, (3) preliminary scoping study for a fuel research laboratory, (4) calculation of energy return on investment, and (5) advanced fuels for future light-water reactors.

develop its methodology for selecting nuclear fuel cycles, it will need to consider evaluation criteria not addressed in the initial screening study that will be important in selecting a nuclear fuel cycle or cycles that industry finds acceptable. Specifically, the report identified the need for broader stakeholder participation, including the nuclear industry, in refining the evaluation criteria, particularly those associated with economics, such as the life-cycle costs of a nuclear fuel cycle.

According to the peer review panel for the initial screening process study, the evaluation criteria did not include any incentives for industry to buy or operate facilities that incorporate any of the fuel cycles that DOE may select and demonstrate. The peer review panel also noted that such incentives for industry are essential. In January 2011, two of the industry groups that participated in the first task order suggested a number of improvements to the collaborative process, including involving industry in periodic peer reviews of DOE's R&D efforts and having industry work with the department to determine the point where DOE funding for technology development should stop and industry funding should begin. DOE officials explained to us that they issued operating procedures in May 2011 that more specifically identified how DOE will collaborate with the nuclear industry under the ID/IQ agreement. These officials explained that the operating procedures are intended to ensure that any new task orders issued under the current ID/IQ agreement will indicate how industry input will help DOE achieve the milestones in its R&D plan. Nevertheless, DOE R&D plan does not provide a strategy for how it will collaborate with the nuclear industry that addresses industry concerns for its involvement over the long term. Without a collaboration strategy to sustain the nuclear industry as a partner in its R&D, DOE may be at risk of developing fuel cycle options that industry does not use. As we have previously reported, collaborative efforts can be enhanced and sustained by engaging in key practices, including (1) defining and articulating a common outcome; (2) establishing mutually reinforcing or joint strategies; (3) identifying and addressing needs by leveraging resources; (4) agreeing on roles and responsibilities; (5) establishing compatible policies, procedures, and other means to operate across agency boundaries; (6) developing mechanisms to monitor, evaluate, and report on results; and (7) reinforcing accountability for collaborative efforts through performance management systems. While our previous report focused on collaboration among federal agencies, we believe that the key practices identified are relevant to the need for improved collaboration between DOE and the nuclear industry in developing nuclear fuel cycles and associated technologies.[21] We note, however, that DOE has an independent role in deciding on a nuclear fuel cycle and associated technologies that best serve U.S. interests in minimizing waste and reducing proliferation and terrorism risks.

DOE's R&D Plan Acknowledges the Need for International Collaboration but Does Not Specify How DOE Will Use Existing Collaborative Agreements with Other Countries

According to DOE's R&D plan, DOE recognizes that international R&D collaboration, at least in the short term, is essential for meeting its objective of developing sustainable nuclear fuel cycles. The plan states that these collaborations may help accelerate technology development and temporarily fill some of the gaps—such as the absence of fast reactors—in the United States' current nuclear R&D infrastructure.[22] While the plan does not discuss in detail any mechanisms for fostering international collaborative R&D efforts to develop sustainable nuclear fuel cycles, DOE officials told us about the collaborative agreements they currently have with other countries. The principal forums that DOE uses for its international R&D collaboration are the following:

- *Multilateral agreements.* DOE, along with other agencies, represents the United States as a member country in several multilateral nuclear energy forums, including IAEA, International Framework for Nuclear Energy Cooperation (IFNEC), Generation IV International Forum, and the Nuclear Energy Agency.[23] For example, the Generation IV International Forum—chartered in 2000 with nine member countries and supported by the Nuclear Energy Agency—allows countries to collaborate on testing the feasibility and performance of advanced nuclear systems in order to make them available for industrial deployment by 2030. In this forum, France, Japan, and the United

[21] GAO, *Results-Oriented Government: Practices That Can Help Enhance and Sustain Collaboration among Federal Agencies*, GAO-06-15 (Washington, D.C.: Oct. 21, 2005).

[22] A fast reactor is a reactor in which the chain reaction is sustained by fast neutrons. These higher energy neutrons can fission all types of uranium and transuranic elements, rather than only the fissile isotopes split in thermal reactors, such as light-water reactors. This allows the fast reactor to transmute (consume) the transuranics. Thus, fast reactors can extract energy from both uranium and transuranic elements.

[23] DOE represents the United States in IFNEC, which is an international forum of 29 member countries, 30 observer countries, and 3 observer organizations, to explore mutually beneficial approaches to ensure that the use of nuclear energy for peaceful purposes proceeds in a manner that is efficient and meets high standards of safety, security, and nonproliferation.

States, are collaborating on two of six prototype nuclear reactor designs, the very-high temperature reactor and the sodium-cooled fast reactor.

- *Trilateral agreement.* France, Japan, and the United States are in the process of establishing a trilateral agreement to develop reprocessing technologies for spent nuclear fuel. Under this agreement, DOE will be allowed access to a French facility to fabricate new forms of nuclear fuel and a Japanese nuclear reactor test facility to recycle spent nuclear fuel. One objective of the agreement is to demonstrate full recycling of nuclear fuel in a fast reactor in Japan. According to a DOE official, this trilateral agreement has been under negotiation for more than 2 years.

- *Bilateral agreements.* DOE's International Nuclear Energy Research Initiative, established in 2001, is a mechanism for entering into bilateral agreements on nuclear energy R&D. DOE enters into these bilateral agreements to (1) develop advanced concepts and scientific breakthroughs in nuclear energy technology, (2) promote collaboration with international agencies and research organizations to improve the development of nuclear energy, and (3) promote and maintain a nuclear science and engineering infrastructure in order to resolve future technical challenges. The goal is to achieve a 50-50 matching contribution from each partner country. DOE currently has active agreements with Canada, France, and the Republic of Korea, as well as with the European Union.

- *Action plans.* DOE has begun to develop action plans to jointly conduct R&D on and share knowledge about key nuclear facilities and technologies. DOE currently has action plans with China, India, Japan, and Russia. These plans identify mutually agreed areas of cooperation and lay out a schedule of events, such as workshops, milestones, and deliverables. For example, the United States has agreed to work with each of these countries separately on developing fast reactors.

These forums that DOE uses for international R&D collaboration indicate that DOE has many opportunities to cooperate with other countries to develop sustainable nuclear fuel cycles. For example, DOE's R&D plan states that it will share research results and leverage U.S. R&D investments with France, Japan, and Russia that are also conducting work on transmutation technologies, which involve using fast reactors to transform highly radioactive material into a less radioactive material. The R&D plan further states that DOE has modeling and simulation capabilities that could be shared with other countries, and that it envisions restarting a nuclear reactor test facility at the Idaho National Laboratory in 5 to 6 years, which could also be shared with other countries.[24]

However, DOE's R&D plan does not fully explain how it will take advantage of these collaborative agreements to advance its efforts to select and demonstrate sustainable nuclear fuel cycles. This is particularly important because these collaborations could help the United States use research facilities in other countries, such as reprocessing and fuel fabrication facilities, as well as advanced reactors. According to DOE's R&D plan, DOE does not currently have adequate nuclear research facilities for developing advanced fuel cycle technologies, and DOE officials estimated that it would take 10 to 15 years to design and construct them. As a result, DOE envisions building two major research facilities—a fast test reactor and a fuel cycle laboratory to test advanced reprocessing and nuclear fuel technologies.[25] DOE has already requested through its ID/IQ agreement preliminary conceptual planning for a nuclear fuel cycle research laboratory. However, as table 2 shows, some of these facilities are already available or are being constructed in other countries, and DOE's plan does not indicate how it might use any of these facilities to further its R&D effort. DOE officials agreed that using the resources of some of these facilities in other countries would help DOE in meeting its R&D objectives, but these officials also explained that obtaining access to these facilities is limited and could constrain ability to conduct R&D in a timely manner.

[24]This facility, the transient test reactor, was used to test nuclear fuels at various stages of the nuclear fuel cycle and was shut down in 1994.

[25]A fast test reactor is a reactor that generates fast neutrons and is intended for use in testing of nuclear fuels rather than commercial power generation.

Table 2: Nuclear Facilities in the United States and in Countries That Have Collaborative Agreements with the United States

Country	Fast reactors		Research and test reactors[a]		Fuel fabrication facilities		Reprocessing facilities	
	Operating	Under construction	Operating	Under construction	Operating	Under construction	Operating	Under construction
China	1[b]		16					
France	1		11	1	1		2	
India	1[b]	1	6					
Japan	2		15			1		1
Russia	2	1	47	1	1		1	
Republic of Korea			2					
United States			41		1	1[c]		
Total	**7**	**2**	**138**	**2**	**3**	**2**	**3**	**1**

Source: Idaho National Laboratory.

Note: The United Kingdom does not have a collaborative agreement with the United States. It does have two operating test/research reactors, two operating fuel fabrication facilities and one under construction, and two operating reprocessing facilities.

[a]Research and test reactors—also called "non-power" reactors—are nuclear reactors primarily used for research, training, and development. These reactors contribute to almost every field of science including physics, chemistry, biology, medicine, geology, archeology, and environmental sciences.

[b]This reactor is also included in the total for operating research and test reactors.

[c]This facility is the Mixed Oxide Fuel Fabrication Facility, which is currently under construction at DOE's Savannah River site in South Carolina.

DOE's R&D plan also does not address how the department will decide between building nuclear research facilities, such as a fast test reactor, and using its existing international collaborative agreements to gain access to planned or existing facilities in other countries. International R&D collaboration has broad support from the Electric Power Research Institute, the Nuclear Energy Agency, and the Blue Ribbon Commission as a way to share the cost of designing and building these facilities. Without specifying how it will use its existing collaborative agreements with other countries, NE may miss opportunities to use the expertise and R&D facilities in these other countries to more efficiently and effectively meet its R&D objectives.

DOE's Office of Nuclear Energy Is Working to Understand and Minimize Proliferation and Terrorism Risks but Faces Challenges and Has Not Formally Coordinated with NNSA

As its R&D plan details, DOE's Office of Nuclear Energy has efforts underway to better understand and minimize nuclear proliferation and terrorism risks and recognizes the challenges associated with these efforts. However, the office has not developed a formal coordination mechanism with NNSA, which is necessary to avoid overlap and duplication in minimizing proliferation and terrorism risks.

DOE Has Undertaken Three Efforts to Better Understand and Minimize Risks of Proliferation and Terrorism, but Faces Challenges

In accordance with its R&D plan, DOE has described three efforts underway to better understand and minimize the proliferation and terrorism risks associated with nuclear fuel cycles: (1) developing and validating a methodology to assess these risks, (2) safeguarding nuclear material, and (3) participating in IFNEC to advance U.S. interests in minimizing these risks.[26]

Developing and Validating a Methodology to Assess Proliferation and Terrorism Risks

According to DOE officials, the department is in the early stages of developing a methodology to examine the proliferation and terrorism risks associated with different types of nuclear fuel cycles as part of its effort to select and demonstrate sustainable nuclear fuel cycles. DOE held a workshop in February 2010 with subject matter experts to obtain their views on what information the department would need to assess nuclear proliferation and terrorism risks related to nuclear fuel cycle options. DOE also held a second workshop in July 2010 that some of the same experts attended, as well as representatives from the nuclear industry and academia to obtain views on its R&D plan. According to DOE officials, its

[26] In its plan, DOE describes four R&D and demonstration areas that we have consolidated into three efforts.

R&D efforts will expand on the internationally developed methodology to assess proliferation and terrorism risks.[27]

In its R&D plan, DOE identified four challenges to developing its own methodology to assess the proliferation and terrorism risks of different nuclear fuel cycles:

- *Quantifying the intent and shifting motivations of adversaries.* The plan stated that it is difficult to develop mathematical methods for quantifying human behavior to predict how adversaries may choose to act. It is also difficult to predict when they might modify their choices based on the actions and behavior of the defenders of the facilities chosen for attack and the outcome of events in relation to these incidents.

- *Addressing threats that change over time.* The plan stated that threats or perceived threats can change drastically over time because of new information or other factors. When the time horizon of a risk assessment takes place over many decades, anticipating future threats presents major challenges.

- *Analyzing the potential effects of policy and technology changes.* Because it will take decades to select and demonstrate nuclear fuel cycles, the plan stated that it will be challenging to analyze policies and technical measures that can change in ways that are difficult to predict.

- *Estimating risks from technologies that have not yet been developed or deployed.* The plan stated that when new technologies are involved, it is difficult to assess the problems these technologies may present before they become operational.

DOE officials told us that once the department develops a risk assessment methodology, it will need to validate it. DOE's R&D plan recognizes three challenges for validating the methodology to assess proliferation and terrorism risks:

[27]The international risk assessment methodology was developed in 2006 as part of the Generation IV International Forum. This forum established an expert group, including officials from DOE's Office of Nuclear Energy and NNSA, to develop a Proliferation Resistance Proliferation Prevention risk assessment methodology.

- *Lack of empirical data on the vulnerabilities of nuclear facilities.* To address this challenge, the plan states that DOE will gather empirical data from various sources, such as the Department of Homeland Security and the Nuclear Regulatory Commission.

- *Lack of information on nuclear fuel cycle options.* There is currently insufficient information on all nuclear fuel cycle options to validate their risks through an assessment methodology, according to a national laboratory expert. To overcome this challenge, DOE plans to apply its risk assessment methodology to theoretical nuclear fuel cycles that might be deployed under a set of assumed conditions.

- *Impediments to obtaining external peer review of the methodology.* To help validate the risk assessment methodology, the plan states that DOE will conduct an external peer review. According to DOE officials, the methodology is likely to rely in part on classified data, but few outside, independent experts in such methodologies have the security clearance that would be needed to review the methodology. To address this challenge, according to a DOE official, DOE has contracted with the National Academy of Sciences to conduct an external peer review of the methodology under secure conditions, which is estimated to be completed by the end of 2012.

Recognizing these challenges, DOE officials told us that any resulting risk assessment methodology should not be the sole basis for assessing whether a particular nuclear fuel cycle would reduce proliferation and terrorism risks.

Safeguarding Nuclear Material

According to the R&D plan, DOE faces two primary challenges in its efforts to help safeguard nuclear material. First, it faces the challenge of developing new concepts for nuclear fuels and nuclear reactors that are cost effective and reliable while producing radioactive materials that are less attractive for proliferation and terrorism. To address this challenge, DOE plans to integrate safety, safeguards, and security features into the design of the nuclear fuel cycle technologies, starting from the earliest conceptual design stages.[28] Second, DOE faces the challenge of designing equipment that can measure and monitor nuclear materials as

[28]Safeguards include an integrated system of physical protection, material accounting, and material control measures designed to deter, prevent, detect, and respond to unauthorized possession, use, or sabotage of nuclear materials.

they move through the different stages of the nuclear fuel cycle. Current technology relies on a time-consuming approach of taking samples of nuclear materials, including lab analysis, which does not allow real-time tracking of the material to prevent diversion, theft or loss of nuclear material. To address this challenge, DOE is continuing to develop technologies to track nuclear material, in close coordination with NNSA, the Nuclear Regulatory Commission, IAEA, and other international partners.

Participating in IFNEC to Advance Nonproliferation Goals

According to DOE's R&D plan, DOE participates in the following three IFNEC efforts to reduce opportunities for nuclear proliferation and terrorism:

- *Nuclear fuel services.* Under this effort, countries with reprocessing capabilities could receive spent nuclear fuel from utilities in other countries, reprocess it, fabricate new nuclear fuel, and send this new fuel back to these utilities.

- *Comprehensive nuclear fuel services.* Comprehensive nuclear fuel services is an approach in which commercially based nuclear fuel cycle services—including fuel leasing, regional or internationally managed interim storage, and disposition of used fuel with the supplier or a third party—are made available on a global basis to countries meeting their nonproliferation responsibilities.

- *Participation in the nonproliferation regime.* Under this effort, DOE provides leadership and technical contributions in international forums associated with nonproliferation.

To date, DOE officials have attended IFNEC meetings in France, Italy, Japan, and Jordan. Thus far, several reports have been issued at the IFNEC working group and ministerial levels, including statements by IFNEC member countries and working group reports on issues such as radioactive waste management and the role of the nuclear industry in ensuring nuclear fuel cycle services.[29]

The Office of Nuclear Energy faces a challenge in supporting U.S. nonproliferation goals through its participation in IFNEC, because the

[29] IFNEC has two primary working groups, one on infrastructure development and the other on reliable fuel services.

office does not have lead responsibility for developing, implementing, and supporting international frameworks and institutions. NNSA and other federal agencies have lead responsibility; thus, the office has limited ability to develop, implement, and support international frameworks.

Office of Nuclear Energy Has Not Established a Formal Mechanism for Coordinating with NNSA on Nuclear Proliferation and Terrorism Issues to Avoid Overlap and Duplication

The Office of Nuclear Energy has taken some actions to address proliferation issues as it moves forward in its efforts to select and demonstrate nuclear fuel cycle options, but the office has not developed a formal mechanism for coordinating its efforts to minimize proliferation and terrorism risks with NNSA, which has lead responsibility within DOE for nonproliferation. According to DOE's R&D plan, the Office of Nuclear Energy is responsible for providing technical expertise and leadership on nuclear technology to the U.S. agencies with overall responsibility for nuclear nonproliferation policy.[30] According to Office of Nuclear Energy and NNSA officials, R&D efforts on understanding and minimizing proliferation and terrorism risks should not be separate from and must support NNSA's work in trying to meet U.S. nonproliferation goals.

The Office of Nuclear Energy has a number of ways in which it informally coordinating with NNSA. According to DOE's R&D plans, the Office of Nuclear Energy has informally worked with NNSA largely through long-standing relationships among researchers and managers that cut across organizational boundaries. According to NNSA officials, this informal coordination is in part possible because the Office of Nuclear Energy and NNSA use the same subject matter experts at the national laboratories. However, these officials noted that when officials and subject matter experts retire or leave either organization, this informal sharing of information may not continue.

Office of Nuclear Energy officials explained that their office has not established a formal coordination mechanism with NNSA because the office has traditionally focused on domestic nuclear issues and NNSA focuses on the international aspects of nuclear proliferation and terrorism risks. However, DOE's R&D plan now includes work that has international implications because the nuclear fuel cycles and associated technologies under consideration by the Office of Nuclear Energy might be adopted by

[30]In addition to NNSA, the Office of Nuclear Energy provides technical assistance to the Department of State, Nuclear Regulatory Commission, and other organizations.

other countries. DOE's R&D plan discusses the need to complete formal coordination mechanisms, such as a memorandum of understanding or coordination committees between the Office of Nuclear Energy and NNSA to coordinate work and to avoid overlap. Office of Nuclear Energy officials told us that they have formed some coordinating groups with NNSA and have begun to discuss developing a memorandum of understanding, but that they have not decided on how best to integrate their R&D with NNSA's nonproliferation efforts. As we have reported, defining organizational roles and responsibilities in formal mechanisms can help agencies strengthen their commitment to work collaboratively by clarifying who will lead or participate in which activities and how decisions will be made.[31]

French and British Experiences in Reprocessing and Recycling Can Provide Insights for U.S. Decision Making

France and the United Kingdom's experiences in developing and operating reprocessing and recycling infrastructures can provide some insights into the decisions DOE may need to make in selecting and demonstrating nuclear fuel cycles and associated technologies.

Reprocessing and Recycling Reduces the Need to Mine Uranium. According to French government officials, reprocessing and recycling plutonium and uranium reduces the need to mine uranium. The amount of uranium needed for nuclear fuel in a reactor depends on how much MOX fuel and reprocessed uranium fuel is used in the nuclear reactors that are licensed for these fuels. According to a 2010 French government report, the current reprocessing and recycling approach in France reduces the amount of uranium needed for nuclear fuel by up to about 17 percent. This report included input from AREVA—the French company responsible for managing all stages of the nuclear fuel cycle, including constructing and operating reprocessing and recycling facilities—and Electricité de France (EdF)—the utility responsible for operating most of the country's commercial nuclear power reactors. The estimate in the report assumes that the 22 French reactors that can use MOX fuel and the 4 French reactors that can use reprocessed uranium fuel use the maximum amount of these fuels—up to 30 percent MOX fuel and 100 percent reprocessed

[31]GAO, *National Security: Key Challenges and Solutions to Strengthen Interagency Collaboration*, GAO-10-822T (Washington, D.C.: June 9, 2010); and GAO-06-15.

uranium fuel in these reactors.[32] According to French government officials, if France were to recycle all of the reprocessed uranium and plutonium it generates from reprocessing, it would further reduce the amount of uranium needed for nuclear fuel by up to almost 25 percent. According to United Kingdom officials, because the country has had limited experience with using recycled nuclear fuels, it has achieved only minimal savings of uranium from its reprocessing and recycling activities.

Recycling consumes some of the plutonium contained in spent nuclear fuel. According to French government officials, recycling results in a net reduction of plutonium. MOX fuel contains about 8.5 percent plutonium, and spent MOX fuel contains about 6 percent plutonium, according to these officials. These officials estimated that, in their current use of MOX fuel, the annual overall quantity of plutonium generated is at least 2.5 metric tons lower than if the same reactors had used conventional enriched uranium fuel. However, reactors that have been licensed to use MOX fuel can only use up to 30 percent of this fuel in a reactor per refueling; the remaining 70 percent or more of the fuel is conventional enriched uranium fuel, which generates plutonium. According to AREVA officials, the decrease of plutonium in MOX fuel is offset by the increase in plutonium resulting from the use of conventional enriched uranium fuel in the reactor. In addition, because France only uses as much plutonium as it creates each year, recycling of plutonium in France does not reduce its current inventory of 35 metric tons of nondefense plutonium. According to AREVA officials, the new generation of nuclear reactors they are developing are designed to use a higher percentage of MOX fuel and thus more plutonium would be consumed and, in turn, less would be generated.

The conditions for plutonium use are different in the United Kingdom because it does not recycle plutonium. As a result, the United Kingdom's reprocessing of domestic spent nuclear fuel has resulted in an inventory of 84 metric tons of nondefense plutonium. The United Kingdom plans to store most of this plutonium until 2120, and it currently considers this plutonium as having no value as an asset. However, the disposition of the United Kingdom's inventory is under review. As part of this ongoing review, the United Kingdom government reported that the review is to

[32]High Committee for Transparency and Information on Nuclear Security, *Avis Sur la Transparence de la Gestion des Matières et des Déchets Nucléaires Produits aux Différents Stades du Cycle du Combustible* (Paris, France: July 12, 2010).

include an assessment of whether the plutonium should be reused as MOX fuel in a new generation of nuclear reactors. The United Kingdom government also reported that recycling plutonium as MOX fuel consumes roughly one-third of the plutonium and significantly degrades the remaining plutonium, making it less attractive for use in a nuclear weapon but more expensive to reprocess a second time.[33] In addition, according to an official from the United Kingdom's Royal Society, the amount of time during which plutonium is maintained in a separated form should be minimized by converting it to MOX fuel as soon as it is feasible to do so, and nuclear reactors should be identified in advance to ensure the use of this MOX fuel.[34]

Reprocessing and recycling spent nuclear fuel is likely to reduce the space needed for a geologic repository, but the size of the reduction is uncertain. Reprocessing and recycling is likely to reduce the space needed for a repository compared with the once-through nuclear fuel cycle because uranium and plutonium are reused rather than disposed of, according to French government officials. On the other hand, subject matter experts we spoke with said that the reduction in the amount of repository space stemming from reprocessing and recycling would depend on how much of the radioactive materials that France considers reusable might ultimately require disposal in a geologic repository. The materials considered reusable are primarily spent MOX fuel, spent reprocessed uranium fuel, and plutonium. Because the disposition of radioactive materials considered reusable is uncertain, a 2006 French law requires, among other things, that the owners of this material, primarily AREVA and EdF, study how they would manage it if it were later defined as waste.[35] According to the law, this may occur if the technologies envisioned for reusing these materials, primarily fast reactors, do not perform as anticipated or if the current reprocessing and recycling processes are abandoned. In discussions leading up to this law, in 2005,

[33]United Kingdom Department of Energy and Climate Change, *Management of the U.K.'s Plutonium Stocks: A Consultation on the Long-Term Management of U.K. Owned Separated Civil Plutonium* (London, England: February 2011).

[34]The Royal Society is the United Kingdom's scientific academy. Its priorities address the future of science in the United Kingdom and beyond. Its working group on the nuclear fuel cycle and nonproliferation released preliminary recommendations from its work on these issues in March 2011, and published its final report October 2011.

[35]Articles of the Planning Act N. 2006-739 of 28 June 2006 Concerning the Sustainable Management of Radioactive Materials and Waste modifying the Environment Code.

the French National Radioactive Waste Management Agency (ANDRA) prepared three scenarios for determining the size of the planned geologic repository.[36] In the first scenario, ANDRA estimated that the planned repository would need about 2 square miles under current plans to dispose of the reprocessing waste that requires geological disposal. In the second scenario, ANDRA estimated that the repository would need about 3.5 square miles if spent MOX fuel and spent reprocessed uranium fuel were also disposed of. In the third scenario, ANDRA estimated that the repository would have needed about 5.4 square miles if France had never reprocessed spent fuel and instead had always relied on a once-through nuclear fuel cycle. However, these calculations do not include waste stemming from the reprocessing and recycling of spent MOX fuel and spent reprocessed uranium fuel. A figure showing the radioactive materials generated by reprocessing and recycling of 1000 metric tons of spent nuclear fuel in France is provided in appendix IV.

The United Kingdom's Nuclear Decommissioning Authority (NDA) is planning to develop a geologic repository for the 470,000 cubic meters of high- and intermediate-level wastes resulting from the operation of its current nuclear reactors.[37] However, the effect of reprocessing and recycling spent nuclear fuel on the amount of space needed for a geologic repository is under review, including whether to dispose of radioactive materials that are being stored but that are potentially reusable, primarily plutonium. In addition, NDA has estimated that it would need to increase the geologic repository currently being planned by about 50 percent to accommodate the spent nuclear fuel generated from nine planned nuclear reactors, if this spent fuel is not reprocessed and recycled into MOX fuel. In contrast, if the spent nuclear fuel from the planned reactors is reprocessed and MOX fuel is fabricated and used in these reactors, NDA anticipates that the geologic repository would only need to increase by 15 percent. However, this latter estimate does not consider the need to dispose of the spent MOX fuel from these proposed new reactors.

[36]These scenarios are based only on the footprint of the disposal areas needed for the waste and not the total area needed for the repository.

[37]The NDA is a government-owned organization with responsibilities for decommissioning and cleaning up the facilities and waste from the United Kingdom's nuclear power infrastructure.

Collocating reprocessing and fuel fabrication facilities would better minimize proliferation and terrorism risks. French government and AREVA officials point to decades of safe and secure operations, but they said that they recognize that, if they were to develop the recycling infrastructure today, they would, among other things, collocate the reprocessing and fuel fabrication facilities to avoid transporting plutonium for a distance of about 600 miles, as they do now. They also noted that they would rely on reprocessing technology designed to keep plutonium in a mixture with uranium that could be used for nuclear fuel, rather than their current process of separating the plutonium from the uranium and other radioactive materials.

According to United Kingdom officials, their current security arrangements provide sufficient protection against the diversion of materials and against terrorism. These arrangements include collocating reprocessing and recycling facilities, as well as subjecting these facilities to stringent security requirements using a multibarrier approach, such as robust storage facilities and armed guards. They also told us that they favored additional efforts to reduce the attractiveness of radioactive materials, particularly plutonium, resulting from reprocessing and recycling. See appendixes III and V for detailed information on these countries' experiences with reprocessing and recycling spent nuclear fuel.

Conclusions

To its credit, DOE has taken a systematic approach to planning for the complex, scientifically challenging process of identifying and selecting sustainable nuclear fuel cycle options and associated technologies by 2020 and demonstrating them by 2050. We are concerned, however, that DOE's initial steps will not be followed by actions needed to sustain its plans over this long period to achieve this goal. In particular, DOE's R&D plan states that the department will continue to evaluate the technological readiness of nuclear fuel cycle options to differentiate among them and to focus development on those that will help meet the R&D plan's schedules and goals. However, neither the R&D plan nor the pilot screening process describe the current readiness of all critical technologies associated with the nuclear fuel cycles or the estimated time and costs for further developing them, or relate technology readiness to R&D schedules and goals. Such estimates are critical to understanding the magnitude of the R&D effort and to measuring progress in developing these technologies. In addition, DOE does not have a long-term strategy for collaborating with the nuclear industry that clarifies the government's and industry's roles and responsibilities. Without such a strategy, DOE cannot be assured that the nuclear industry will accept and use the technologies that it develops.

Furthermore, DOE has not specified in its R&D plan how it will use its collaborative agreements with other countries to advance its R&D efforts to develop sustainable nuclear fuel cycles over the longer term. As a result, DOE may miss opportunities to use facilities and expertise in other countries to more efficiently and effectively meet its R&D goals. Finally, DOE has not developed a formal mechanism for coordinating its efforts to develop sustainable nuclear fuel cycles with NNSA, which has lead responsibility in DOE for minimizing proliferation and terrorism risks—a critical factor in selecting new fuel cycles. DOE officials said they recognize the need for coordination with NNSA and have done so informally. They also said they have begun to discuss developing a memorandum of understanding with NNSA. As we have reported, defining organizational roles and responsibilities in formal mechanisms can help agencies strengthen their commitments to work collaboratively by clarifying who will lead or participate in which activities and how decisions will be made. Formal mechanisms are also important to sustaining coordination over the long term and avoiding overlap and duplication.

Recommendations for Executive Action

For the Office of Nuclear Energy to reach its goal of selecting sustainable nuclear fuel cycles and associated technologies by 2020 and demonstrating them by 2050, we recommend that the Secretary of Energy direct the Assistant Secretary of the Office Nuclear Energy to take the following actions:

(1) Revise the R&D plan to

- include the current readiness levels of the technologies associated with the fuel cycle options being considered and the estimated time and cost for developing these technologies in relationship to the R&D plan's schedules and goals,
- include a strategy for sustaining long-term collaboration with the nuclear industry, including a formal mechanism that clarifies the role industry will have at critical points in selecting fuel cycle options and associated technologies, and
- specify how DOE will use collaborative agreements with other countries to advance its R&D efforts and use available facilities and expertise in these other countries to more efficiently and effectively meet its R&D goals.

(2) Complete a memorandum of understanding with NNSA to help ensure that DOE's Office of Nuclear Energy and NNSA coordinate their work to avoid overlap and duplication in their efforts to minimize proliferation and terrorism risks.

Agency Comments and Our Response

We provided a draft of this report to the Department of Energy for review and comment. In written comments on a draft of this report, the department generally agreed with the first three of our recommendations and did not rule out the future use of a formal memorandum of understanding between its Office of Nuclear Energy and NNSA, as we also recommended.

Specifically, with respect to our recommendation to include the current readiness levels of the technologies associated with the fuel cycle options being considered, DOE stated that it would incorporate lessons learned from its assessment of technology maturity as part of an initial screening of fuel cycle options in fiscal year 2010 to a follow-on screening study planned for fiscal year 2013. DOE stated that it would then incorporate technology readiness information developed and evaluated from the fiscal year 2013 screening into revisions to its R&D plan. Furthermore, DOE also stated that it will pay greater attention to defining technology readiness and the costs and time needed to improve that readiness for specific candidate technologies. Regarding our recommendation to include a strategy for sustaining long-term collaboration with the nuclear industry, DOE indicated that it would clarify its intentions for the nuclear industry's engagement over the long term as part of its revisions to its R&D plan. With respect to our recommendation to specify how it will use collaborative agreements with other countries to advance its R&D efforts, DOE acknowledged that its R&D plan does not provide details regarding approaches for how international collaboration will advance its R&D efforts but stated that these details are available in other documents. We recognize that the information on international collaboration may be available in other documents, but we continue to believe that DOE needs to incorporate this information as part of its revisions to its R&D plan to provide a comprehensive roadmap to ensure that it will take advantage of opportunities to use facilities and expertise in other countries to more efficiently and effectively meet its R&D goals.

DOE did not rule out the future use of a formal memorandum of understanding between its Office of Nuclear Energy and NNSA to help ensure that they coordinate to avoid overlap and duplication in their efforts to minimize proliferation and terrorism risks. DOE provided examples of how the two offices are collaborating on nonproliferation issues and stated that while it did consider using a memorandum of understanding to formalize coordination, existing efforts already promote significant teamwork. Our report noted these ongoing collaborations, but we continue to believe that a memorandum of understanding would help ensure that the efforts between the two organizations do not lead to overlap and duplication. Our report noted that defining organizational roles and responsibilities in formal mechanisms can help agencies strengthen their commitment to work collaboratively by clarifying who will lead or participate in which activities and how decisions will be made.

DOE also provided technical comments, which we incorporated as appropriate. DOE's letter and our response are in appendix VI.

As agreed with your offices, unless you publicly announce the contents of this report earlier, we plan no further distribution until 30 days from the report date. At that time, we will send copies to the Secretary of Energy, appropriate congressional committees, and other interested parties. In addition, the report will be available at no charge on the GAO Web site at http://www.gao.gov.

If you or your staff have any questions about this report, please contact me at (202) 512-3841 or aloisee@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix VII.

Gene Aloise
Director, Natural Resources and Environment

Appendix I: Objectives, Scope, and Methodology

We reviewed the (1) approach the Department of Energy (DOE) is taking to select and demonstrate sustainable nuclear fuel cycles and associated technologies; (2) efforts DOE is making to understand and minimize nuclear proliferation and terrorism risks associated with nuclear fuel cycles and associated technologies; and (3) experiences of France and the United Kingdom in reprocessing and recycling spent nuclear fuel that may be useful to the United States in selecting sustainable nuclear fuel cycles and associated technologies.

To address the first objective, to review the approach DOE is taking to select and demonstrate sustainable nuclear fuel cycles and associated technologies, we analyzed pertinent DOE documents, including DOE's "roadmap" for developing advanced recycling technologies and draft and final versions of the plans implementing the roadmap. We refer to the roadmap and the implementation plans collectively as DOE's research and development (R&D) plan.[1] We also interviewed DOE program managers from the nuclear fuel cycle R&D programs associated with the development and implementation of the nuclear fuel cycle objective in the roadmap. We also visited DOE's Idaho National Laboratory (INL), which is the lead laboratory for DOE's Office of Nuclear Energy, to conduct semi-structured interviews with managing officials to assess the status of fuel cycle R&D. We also obtained and reviewed documents prepared by INL on nuclear fuel cycle research.

In addition, to obtain the nuclear industry's views on collaboration with DOE and the usefulness of DOE's R&D plan for them, we interviewed representatives from the six industry groups and analyzed documents we obtained from four of these groups. The six industry groups (with their partners) are the following:

- AREVA group, which includes AREVA Federal Services, LLC; Battelle Memorial Institute, Babcock and Wilcox Technical Services Group, Inc.; Japan Nuclear Fuel Limited; URS Corporation; and Duke Energy Corporation.

[1]DOE's R&D plan included four objectives: (1) selecting and demonstrating sustainable fuel cycles and associated technologies; (2) understanding and minimizing nuclear proliferation and terrorism risks; (3) developing technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors; and (4) developing improvements in the affordability of new reactors to enable nuclear energy to help meet the administration's energy security and climate change goals. Our review addressed the first two objectives.

- CH2M Hill, Inc.
- ENERCON group, which includes Enercon Services, Inc.; Entergy Corporation; S.M. Stoller Corporation; and ANATECH Corporation.
- EnergySolutions group, which includes EnergySolutions, LLC; Atomic Energy of Canada Limited; Booz Allen Hamilton, Inc.; Nuclear Fuel Services, Inc. (a subsidiary of Babcock and Wilcox Technical Services Group, Inc.); United Kingdom National Nuclear Laboratory; Exelon Nuclear Partners (a Division of Exelon Corporation); International Nuclear Services Limited; Sargent and Lundy, LLC; Talisman International, LLC; Teledyne Brown Engineering, Inc.; Columbia Basin Consulting Group, LLC; North Wind, Inc.; and TerranearPMC, LLC.
- General Electric Hitachi group, which includes GE Hitachi Nuclear Energy Americas, LLC; Ernst and Young Global Limited; Fluor Corporation; Lockheed Martin Corporation; and E.I. du Pont de Nemours and Company.
- Shaw group, which includes Shaw Environmental and Infrastructure, Inc.; Westinghouse Solutions, Inc.; and Exelon Corporation, Longenecker and Associates, Inc.

We also conducted semi-structured interviews with representatives from these groups as well as with representatives from two major U.S. utilities—the Tennessee Valley Authority and Duke Energy—of the 26 operating in the United States to obtain their views on their collaboration with DOE and the usefulness of DOE's plan to them. We selected these two utilities because they were two companies with which DOE has discussed buying mixed oxide (MOX) fuel from DOE's Mixed Oxide Fuel Fabrication Facility, which is currently under construction at DOE's Savannah River site in South Carolina. We also conducted semi-structured interviews with organizations that represent the nuclear industry—the Nuclear Energy Institute, a policy organization for the nuclear energy and technology industry, and the Electric Power Research Institute, an independent nonprofit organization that provides R&D relating to the generation, delivery, and use of electricity.

We also conducted semi-structured interviews with five subject matter experts who could provide a range of views on reprocessing and recycling spent nuclear fuel and on DOE's R&D plan. Because we used a nonprobability sample of experts to speak with and we did not attempt to reach consensus among these experts, the information we obtained from these experts cannot be generalized to all experts, but the interviews provided us with information on the perspectives of various experts. To select these experts, we reviewed presentations given before the Blue Ribbon Commission on America's Nuclear Future, and from these presentations identified experts who had presented relevant information; we also reviewed the literature to identify subject matter experts who had conducted extensive research on relevant issues and interviewed some of these individuals; and we interviewed experts who were recommended by other experts and government officials. The experts we interviewed for this and the other objectives included academics, retired government officials, ex-industry officials, and other individuals with extensive knowledge of these issues. We also reviewed testimonies and presentations delivered before the Blue Ribbon Commission and reports issued by the commission.

To analyze DOE's R&D work with international partners and obtain their views on DOE's international collaborations as DOE developed its implementation plans, we spoke with government officials from France and the United Kingdom on their R&D collaboration with DOE, and participated in an international conference organized by the OECD–NEA and sponsored by the International Atomic Energy Agency and the European Commission. This conference, held in November 2010, focused on, among other things, information exchanges on scientific and strategic and policy developments in the field of reprocessing and recycling.

To address the second objective, to review the efforts DOE is taking to better understand and minimize nuclear proliferation and terrorism risks with nuclear fuel cycles and their associated technologies, we obtained and reviewed pertinent documents from the Office of Nuclear Energy, the National Nuclear Security Administration (NNSA) and INL. We also interviewed cognizant Office of Nuclear Energy officials, as well as officials from NNSA and the Department of State, which are lead agencies for proliferation and terrorism risks. We also conducted semi-structured interviews with experts at INL and spoke with two experts from Brookhaven and Los Alamos National Laboratories, who are involved in understanding and minimizing proliferation and terrorism risks. Because we used a nonprobability sample of 20 experts at national laboratories to speak with, the information we obtained from these experts cannot be generalized to all experts at the national laboratories, but the interviews provided us with information on the perspectives of various experts from the national laboratories. We also examined DOE's participation in the International Framework for Nuclear Energy Cooperation (IFNEC).

Moreover, we participated in DOE's Nuclear Energy Enabling Technology program workshop, held in July 2010, to observe how the Office of Nuclear Energy interacts with national laboratory officials, NNSA, industry, and subject-matter experts on proliferation and terrorism issues.

We also obtained documents from, and conducted semi-structured interviews with, representatives from the six nuclear industry groups to obtain their views on their collaboration with DOE for understanding and minimizing proliferation and terrorism risks. We also spoke with government representatives from other countries to understand their concerns about proliferation and terrorism risks. In addition, we interviewed officials from the French atomic energy commission, *the Commissariat ál'Énergie Atomique* (CEA), who participate in IFNEC to learn more about their perception of IFNEC's role in the international nonproliferation arena.

In addition, we conducted individual semi-structured interviews with 10 subject matter experts in the proliferation and terrorism field. We interviewed these experts to assess information received from DOE and the national laboratories. However, we did not attempt to reach consensus among these experts. Moreover, while in the United Kingdom, we conducted a semi-structured interview with four experts from the United Kingdom's Royal Society who are working on a report to assess proliferation and terrorism challenges for the future of nuclear power and management of spent nuclear fuel. Furthermore, during the international OECD-NEA conference, we obtained other countries' views on proliferation matters.

To address the third objective, to review the experiences of France and the United Kingdom in reprocessing and recycling spent nuclear fuel that may be useful to the United States in selecting nuclear fuel cycles and associated technologies, we reviewed relevant documents about their nuclear energy systems, and visited these countries to observe their experiences; obtain additional documents; and interview government, nuclear industry, and utility representatives who oversee and manage the reprocessing and recycling infrastructures. We also interviewed six subject matter experts in the United States who are familiar with the reprocessing and recycling process in these countries. We prepared appendixes III and IV (for France), and V (for the United Kingdom) reflecting these countries' experiences, which we sent to their government officials to review for technical accuracy. We made changes, as appropriate, to incorporate their comments, but we did not independently verify statements of law provided by these reviewers. We selected France and the United Kingdom because they are among the few countries that have decades of experience in reprocessing and recycling spent nuclear fuel.

In France, we spoke with officials from government agencies, such as the Ministry of Foreign Affairs, and the General Directorate for Energy and Climate Change, which is part of both the Ministry of Industry and New Technologies and the Ministry of Ecology, Sustainable Development, Transport and Housing. We also conducted semi-structured interviews with officials from the French nuclear operator, AREVA, and from the French utility, Electricité de France (EdF) to learn about their operating experiences and outcomes of reprocessing and recycling.

We also visited the reprocessing facilities at AREVA's La Hague site and the MOX fuel fabrication facility at AREVA's Marcoule site and conducted semi-structured interviews with these facilities' managers. To observe how France conducts its R&D on advanced technologies, we visited CEA's R&D facilities at Marcoule and AREVA's pilot testing facility at La Hague, where we spoke with researchers and engineers. We also interviewed two subject-matter experts on the French reprocessing and recycling experience.

We also reviewed data from and conducted interviews with AREVA and EdF officials to obtain information on the reprocessing and recycling processes in France and the radioactive material that is generated by these processes. We also consulted with experts from the Oak Ridge National Laboratory on our analysis of the information obtained from the French officials. In addition, we asked four subject-matter experts to provide us with an additional perspective on waste generated by reprocessing and recycling in France. We prepared a separate appendix illustrating the facilities and processes involved in reprocessing and recycling and the radioactive material generated by these processes, which we sent to industry officials to review for technical accuracy (see app. IV). We made changes, as appropriate, to incorporate their comments.

In the United Kingdom, we spoke with officials from the Nuclear Decommissioning Authority and the Department of Energy and Climate Change. To observe reprocessing and recycling operations, we visited the United Kingdom facilities at Sellafield—the Thermal Oxide Reprocessing Plant and the Sellafield MOX fuel fabrication facilities—and spoke with facility managers. To observe how the United Kingdom conducts its R&D work on advanced technologies, we visited its National

Nuclear Laboratory, and we spoke with laboratory officials and researchers. We also interviewed seven experts—three subject-matter experts and four members from the United Kingdom's Royal Society—who are knowledgeable about the United Kingdom's reprocessing and recycling experiences.

In addition, we interviewed officials from international organizations such as OECD-NEA, the International Atomic Energy Agency and the World Nuclear Association to obtain an international perspective on reprocessing and recycling.

We conducted this performance audit from May 2010 through October 2011, in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Appendix II: Significant R&D Challenges in Selecting and Demonstrating Nuclear Fuel Cycles

In its R&D plan, DOE has divided its R&D for selecting and demonstrating nuclear fuel cycles into eight technical areas and identified associated challenges. The following discusses some of the significant challenges the plan identified in each area.

Systems analysis. This area refers to the development of computer modeling and simulation to improve understanding of the interdependences between fuel cycle subsystems and associated technologies. According to DOE's R&D plan, there are two potential challenges: (1) rapidly create and deploy verified and validated modeling and simulation capabilities essential for the design, implementation, and operation of future nuclear energy systems with the goal of improving U.S. energy security and (2) use systems analysis to integrate R&D results from across the eight technical areas.

Fuel resources. DOE will conduct research in this area to better understand the availability of uranium and other nuclear fuel materials to help inform decisions on choosing nuclear fuel cycles. According to DOE's R&D plan, the potential challenge to this work is the ability to extract uranium from unconventional sources, such as seawater, including gathering reliable data on the feasibility and cost of this extraction.

Fuel development. This area focuses on research to examine a variety of nuclear fuels to support the three nuclear fuel cycle categories.[1] DOE identified potential challenges associated with this research, including (1) significantly increasing the performance of nuclear fuels by extending the time for fissioning and (2) fabricating fuel with minimal waste generation.

Separations. This technical area focuses on developing new separations (i.e., reprocessing) methods that enable the recycling and/or transmutation of key nuclear fuel constituents (e.g., actinides). These methods must be economical (i.e., involve minimal processing); minimize waste streams and volumes; and enable the effective safeguarding of fissile material. DOE identified several challenges associated with this technical area, such as capturing off-gases resulting from reprocessing

[1]These categories are the once-through fuel cycle, modified open fuel cycle, and full recycle fuel cycle.

and developing separation processes that are more proliferation resistant for minor actinides.

Waste forms. This technical area focuses on developing new technologies for mixing high-level radioactive waste with different materials, such as ceramics, glass, glass-ceramics, and metals, to derive a waste form that can maintain stability and durability under long-term exposure to high levels of radiation, among other things, and to understand their performance in complex geologic settings. Among the challenges DOE identified are significantly reducing the volume of high- and low-level wastes and improving the durability of waste forms containing the most radiotoxic (and nonradioactive toxic) components to allow for a wide range of disposal options.

Storage and disposal. In this area, DOE plans to conduct research to identify storage and disposal alternatives and develop technology to enable the storage, transportation, and disposal of spent nuclear fuel and wastes generated by existing and future nuclear fuel cycles. Challenges DOE identified in its R&D plan include providing a sound technical basis for absolute confidence in the safety and security of long-term storage, transportation, and permanent disposal of used nuclear fuel and wastes from the nuclear energy enterprise and integrating waste management with no or minimal radioactive releases from storage and disposal systems.

Transmutation technologies. This technical area focuses on developing systems including nuclear reactors that would transmute radioactive materials recovered from spent fuel to significantly reduce their radioactivity. According to DOE's R&D plan, the challenges presented in this area include developing transmutation options that meet a broad range of fuel cycle strategies and developing transmutation options that efficiently generate electricity at a cost similar to that of light-water reactors.

Materials, protection, control, and accountability technology. This research area focuses on developing new processes and technologies to account for and protect nuclear materials from proliferation and terrorism risks. According to DOE's R&D plan, challenges include developing online, real-time, continuous accountability instruments and techniques that significantly improve the ability to inventory fissile materials in domestic fuel cycle systems in order to detect diversion and prevent misuse.

Appendix III: The French Experience in Reprocessing and Recycling Spent Nuclear Fuel

According to French government and nuclear energy officials and subject matter experts, France has decades of experience with reprocessing and recycling spent nuclear fuel. This appendix discusses (1) France's nuclear energy industry and the relevant oversight entities and (2) France's experiences with reprocessing and recycling facilities.

Oversight of Nuclear Energy

The primary government body involved in France's nuclear power infrastructure and policy is its General Directorate for Energy and Climate Change, which is part of both the Ministry of Industry and New Technologies and the Ministry of Ecology, Sustainable Development, Transport and Housing. France's Alternative Energies and Atomic Energy Commission, known as *the Commissariat à l'Energie Atomique et aux Energies Alternatives* (CEA), is responsible for, among other things, all areas of nuclear technology research. In addition, the French company, AREVA, is responsible for managing all stages of the nuclear fuel cycle, including constructing and operating reprocessing and recycling facilities.[1] The French nuclear utility, known as Electricité de France (EdF), is responsible for operating the country's commercial nuclear power reactors. AREVA and EdF were previously wholly owned by the French government but now operate as private companies. However, the French government holds a more than 80 percent ownership share of each company. The French national radioactive waste management agency, known as the Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA), is constituted as a public, industrial, and commercial establishment responsible for conducting all operations relating to the long-term management of radioactive waste. Nuclear safety issues are regulated by the Nuclear Safety Authority.

Reprocessing and Recycling Facilities and Operating Experiences

According to documents we reviewed, French government and nuclear industry officials, and subject matter experts, France's nuclear power infrastructure produces about 75 percent of its electricity needs. This infrastructure includes facilities to reprocess and recycle spent nuclear fuel. The discussion below describes these facilities—including (1) reprocessing facilities, (2) a uranium reenrichment facility, (3) fuel

[1]CEA originally established Compagnie générale des matières nucléaires (COGEMA) in 1976 for these operations, and this organization was later renamed AREVA. Throughout this appendix we use the organization's current name.

fabrication facilities, and (4) reactors that use recycled nuclear fuel—and their operating experiences.

Reprocessing Facilities and Operating Experiences

Under CEA, France has developed reprocessing facilities in two locations. In 1953, CEA built its first reprocessing plant at one of its research sites—Marcoule—in southeastern France. This facility, the Usine de Plutonium (UP) 1, used for military purposes, was shut down in 1997. In 1967, CEA built its first reprocessing facility for commercial spent nuclear fuel—UP2-400, which was capable of processing up to 400 metric tons annually of spent nuclear fuel—at La Hague, a site along the Normandy coast. This reprocessing facility was shut down in 2004 after it had reprocessed about 28,000 metric tons of spent nuclear fuel. The UP2-400 had contracts with neighboring European countries and Japan for reprocessing services for the spent fuel produced from their commercial nuclear reactors.[2] In addition, in 1981, to meet the growing demand for reprocessing from nuclear utilities in other countries, primarily Germany and Japan, AREVA was authorized to construct other reprocessing plants at La Hague.[3] It began operations in 1990, at the UP3, which can reprocess up to 900 metric tons of spent nuclear fuel annually, and in 1994, at the UP2-800, which can reprocess up to 800 metric tons annually. Nuclear utilities in other countries substantially paid for the construction of the UP3 facility, and EdF paid for the construction of UP2-800 facility.

In the past few years, the UP3 and UP2-800 facilities have been reprocessing spent nuclear fuel from EdF and from utilities in other countries at an average of about 1,050 metric tons annually, or about 65 percent of the combined capability of these facilities, according to AREVA officials. Until 2009, EdF shipped about 850 metric tons of its spent nuclear fuel to La Hague each year for reprocessing—more than half of the about 1,250 metric tons that EdF reactors produce annually. AREVA officials told us that it is their policy to limit the amount of spent nuclear fuel that they reprocess annually to the amount of plutonium needed to fabricate enough MOX fuel to meet the needs of their utility customers, including EdF and nuclear utilities in other countries. These officials

[2]French law requires the radioactive waste resulting from reprocessing spent fuel from nuclear utilities in other countries to be returned to these utilities.

[3]Germany decided to abandon its reprocessing facility in 1989, and Japan started active testing of its own reprocessing facility in 2006.

explained that this reprocessing strategy prevents creation of surplus plutonium. Importantly, this strategy does not allow France to reduce its inventory of plutonium, which is about 35 metric tons of domestic, nondefense plutonium.[4] In 2010, EdF increased shipments of spent nuclear fuel to AREVA for reprocessing from 850 metric tons to 1,050 metric tons because it needed more MOX fuel for an expanded number of reactors that are capable of using this fuel. AREVA officials told us they expect to reprocess 1,500 metric tons of spent nuclear fuel per year by 2015, given anticipated demands from EdF and nuclear utilities in other countries.

Uranium Reenrichment Facility and Operating Experience

France reenriches some of the uranium that is obtained through reprocessing (reprocessed uranium) to fabricate reprocessed uranium fuel. This fuel is used by EdF and by nuclear utilities in other countries that send their spent nuclear fuel to France for reprocessing. Before 2004, most of the reenrichment was carried out by the Urenco Company in the Netherlands. Between 2004 and 2010, the reenrichment was conducted at the JSC Siberian Chemical Combine in Seversk, Russia: EdF sent about 500 metric tons of reprocessed uranium to this facility. French government officials explained that it was necessary to send its reprocessed uranium to these facilities in other countries because the reenrichment process requires a technology that does not currently exist in France. However, these officials explained that AREVA is currently constructing a reenrichment line at its newly started George Besse II enrichment facility, located at its Tricastin site in southeastern France, which will use a technology that will allow AREVA to reenrich reprocessed uranium. AREVA plans to begin operating this line in 2012.

Fuel Fabrication Facilities and Operating Experiences

France has operated two MOX fuel fabrication facilities and one reprocessed uranium fuel fabrication facility. In 1989, CEA started fabricating MOX fuel for light-water reactors at its facility in Cadarache, located in southeastern France, for EdF and then for nuclear utilities in Germany and Switzerland.[5] According to French government officials, this facility was shut down in 2003 because the cost of upgrading the facility to meet new safety standards, especially seismic safety standards, could

[4]In France, the production of plutonium through reprocessing for military use ceased in 1993—about 5 metric tons of plutonium from defense activities currently remain in storage along with the 35 tons from nondefense activities.

[5]This facility had fabricated MOX fuel for France's fast reactors before 1989.

not be justified. In 1995, AREVA constructed a new MOX fuel fabrication facility, Melox, at the Marcoule site. Initially, in 1997, the Melox facility was licensed for a capacity to fabricate 100 metric tons of MOX per year; in 2003, the capacity was increased to 145 metric tons per year; and in 2007, it was increased to 195 metric tons per year, although it is not yet operating at this level. According to AREVA officials, the capacity was first increased to 145 metric tons because of the increased demand for MOX fuel from nuclear utilities in other countries, primarily Germany and Japan, and increased again to 195 metric tons to meet the anticipated demand for MOX fuel, primarily from EdF.

To fabricate reprocessed uranium fuel, AREVA operates the Franco-Belgian Fuel Fabrication facility in southeastern France. The production line devoted to fabricating this fuel began operations in 1993; it has the capacity to fabricate about 150 metric tons annually and has been producing about 80 metric tons annually.

Reactors Using Recycled Fuel and Operating Experiences

According to French government officials we spoke with, the government, through CEA, AREVA, and EdF, initially intended to use the uranium and plutonium resulting from reprocessing as fuel for a fast reactor program.[6] Development of fast reactors began in the early 1960s, and two such reactors were built and operated. The 233 megawatt (MW) Phénix fast reactor operated between 1974 and 2009 and the 1,200 MW Super-Phénix operated between 1986 and 1998.[7] These reactors were used to test nuclear fuels, including fuel fabricated from the uranium and plutonium that resulted from reprocessing. However, according to subject matter experts in France, by the late 1980s, financial, technical, and administrative barriers halted the deployment of fast reactors. Without the fast reactor option, EdF decided to modify some of its 900 MW nuclear reactors to accept MOX fuel, and the first reactor licensed to use this fuel began operating in 1987. Currently, 21 of EdF's 58 nuclear reactors have been licensed to use MOX fuel, another reactor has been licensed to use MOX fuel but has not yet used it, and EdF is seeking approval to use MOX fuel in two more reactors.[8] With respect to reprocessed uranium

[6]According to AREVA officials, they expect to use reprocessed uranium or depleted uranium—a byproduct of the uranium enrichment process—mixed with plutonium for the fast reactor fuel.

[7]A megawatt is 1 million watts—a watt is a basic unit of measurement of electrical power.

[8]EdF has 34 reactors that each generates 900 MW of electricity, 20 reactors that generate 1,300 MW, and 4 reactors that generate 1,450 MW.

fuel, 4 of EdF's 58 reactors—each generating 900 MW—are licensed to use this fuel. EdF began testing the use of this fuel in 1987 and started using it full time in 1994. According to an EdF official, EdF has enough reenriched reprocessed uranium to fabricate fuel for use in the four reactors that use it for the next 20 years. However, the official explained that EdF will continue to have AREVA reenrich reprocessed uranium because EdF views this material as a strategic resource that EdF could use in additional reactors if the price of conventional enriched uranium fuel increases enough to make it economically feasible to do so.

In January 2006, the President of France announced a policy to develop a prototype commercial fast reactor by 2020, a policy that was subsequently enacted into law. As part of this new effort, CEA will begin designing a fast reactor for demonstration by 2020 and commercial deployment by 2035.[9] According to CEA officials, the reactor is intended to make better use of uranium resources, including the inventory of depleted and reprocessed uranium; test the capability of the reactor to consume radioactive material, including plutonium; and demonstrate the usefulness of this reactor for commercial deployment. According to these officials, the uranium and plutonium resulting from the reprocessing of spent MOX fuel is expected to be used as the primary fuel for this reactor, and additional reprocessing and fuel fabrication facilities would likely be needed to support this program.

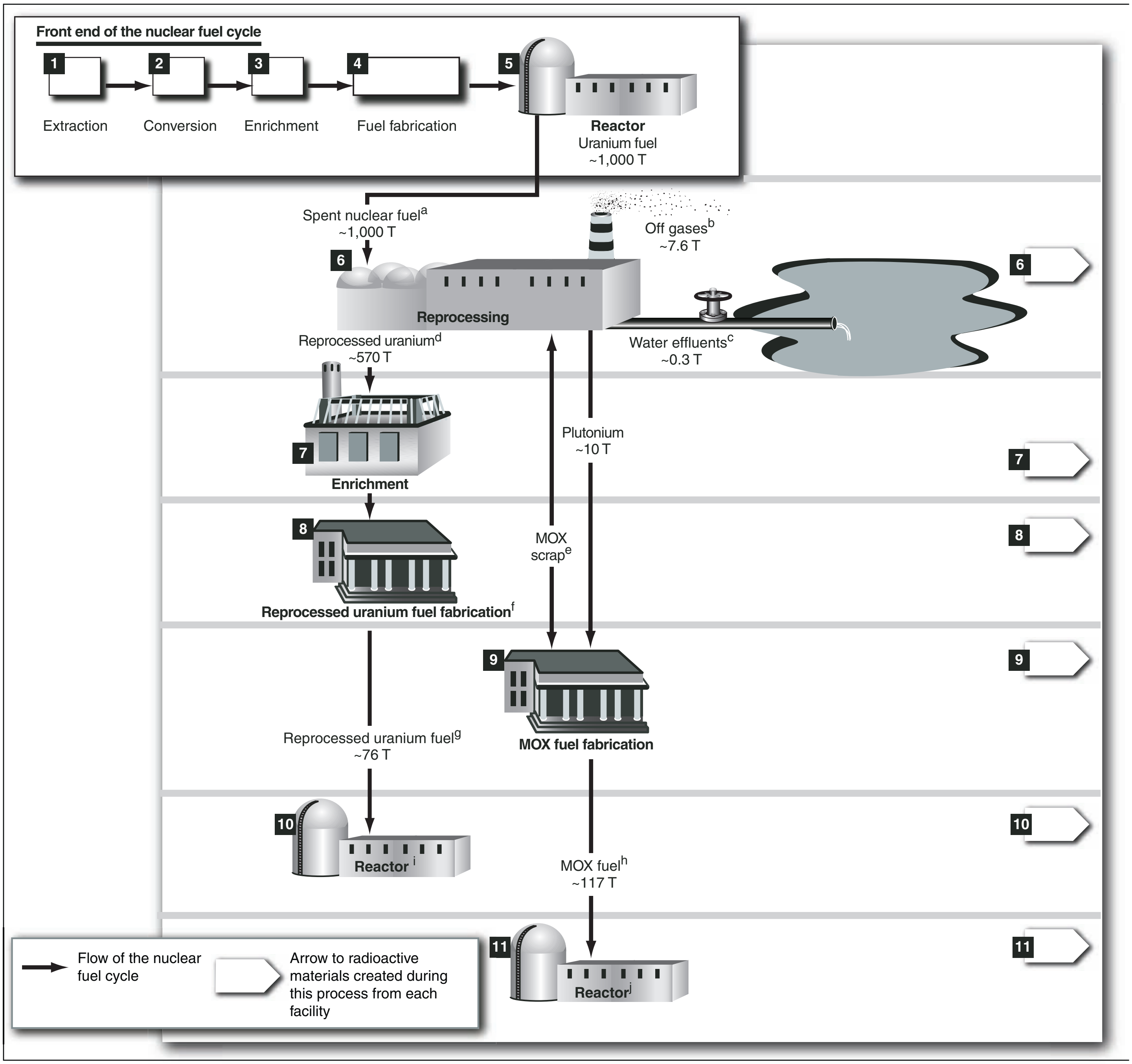
[9] This reactor—the Advanced Sodium Technological Reactor for Industrial Demonstration—is planned to be a 600 MW prototype fast reactor.

Appendix IV: The French Reprocessing and Recycling Process and the Resulting Radioactive Material

Figure 2 illustrates the process used in France to reprocess and recycle 1,000 metric tons of spent nuclear fuel and the radioactive material that is generated from this process. The figure is in two parts: page 52 shows the steps involved in reprocessing and recycling spent fuel, and page 53 shows the radioactive materials resulting from these steps and France's consideration of these materials as reusable or as waste.

As shown on page 52, facility 6, the reprocessing facility, produces, among other radioactive materials, reprocessed uranium and plutonium, and these two materials follow separate recycling pathways for use as fuel in nuclear reactors; the arrows pointing to page 53 show the resulting radioactive material generated by these pathways. As the figure shows, the reprocessed uranium is sent through facility 7 for re-enrichment; through facility 8, where it is fabricated into reprocessed uranium fuel; and to facility 10, where it is used as fuel in a reactor licensed to use the fuel. The plutonium is sent through facility 9, where it is fabricated into MOX fuel; and to facility 11, where it is used as fuel in a reactor licensed to use the fuel. As shown on page 53, reprocessing and recycling generate a variety of radioactive material that may or may not be reused.

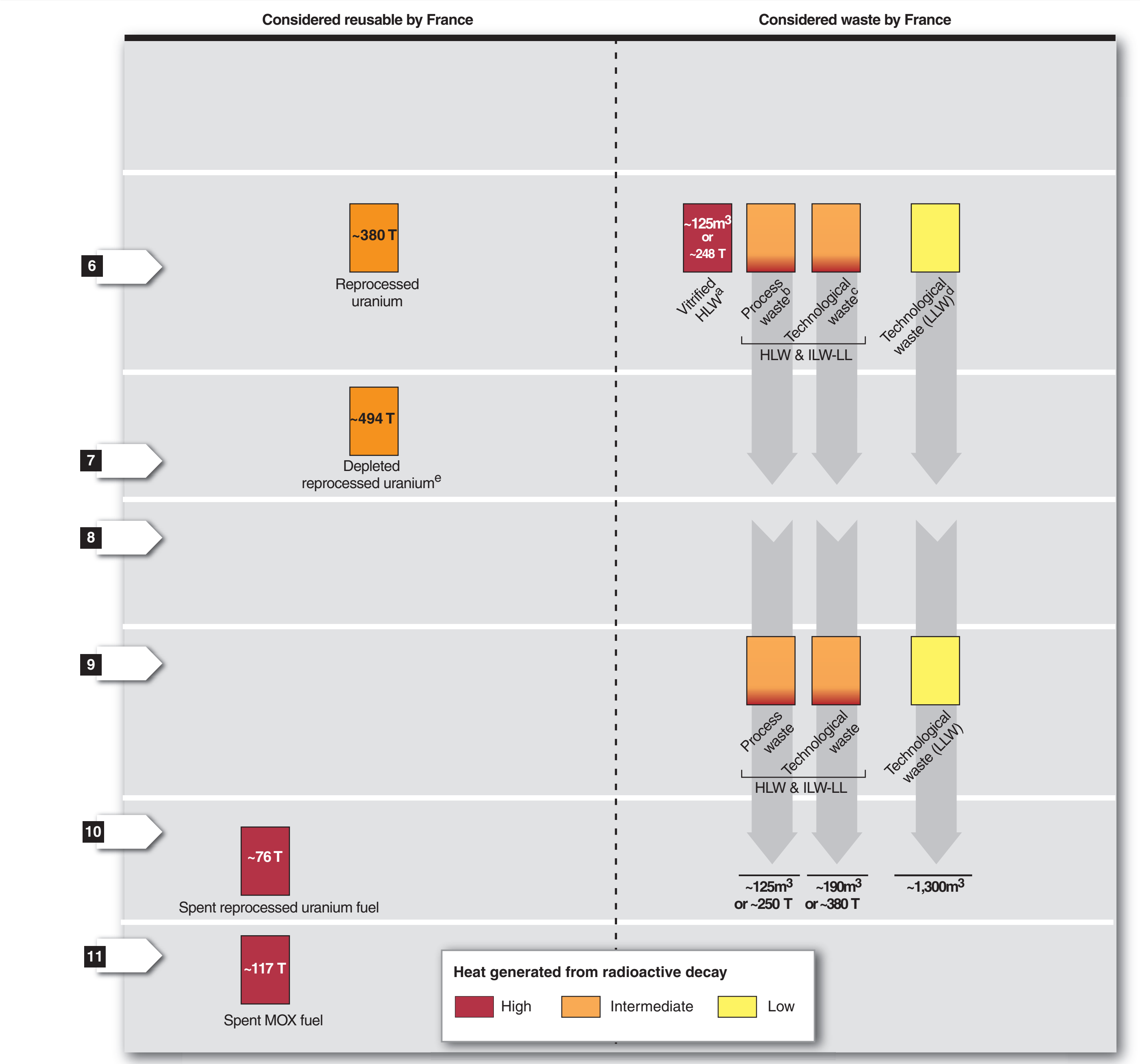
Figure 2 side A: Reprocessing and Recycling Process in France and the Resulting Radioactive Materials (continued on next page)



Sources: GAO analysis of information provided by AREVA, EdF and Oak Ridge National Laboratory.

(continued on next page)

Figure 2 side B: Reprocessing and Recycling Process in France and the Resulting Radioactive Materials (continued from previous page)



(continued from previous page)

Notes:

1. The numbers in figure 2 are based on reprocessing and recycling 1,000 metric tons of spent nuclear fuel. This fuel is assumed to have initially been enriched to 4.2 percent of uranium-235, produced 55 gigawatt days of energy per ton of uranium, and been stored in water pools for 4 years prior to reprocessing.

2. France relies on a radioactive waste classification system that divides radioactive waste into four categories—high-level, intermediate-level, low-level, and very low-level—that represent the degree of radioactivity that this waste generates. These categories are subdivided into three categories based on the length of time the radioactivity of the waste will threaten human health and the environment—long-lived (more than 30 years), short-lived (less than 30 years), and very-short-lived (less than 100 days). The figure does not show very low-level very short-lived waste. France operates surface facilities to dispose of very low-level short-lived waste, and low- and intermediate-level short-lived radioactive waste. France is investigating geologic disposal options for high-level waste and low- and intermediate-level long-lived waste and subsurface disposal options for low-level long-lived waste. (In general, U.S. radioactive waste classes A, B, and 75 percent of class C waste would be classified in France as low- and intermediate-level short-lived waste, and the other 25 percent of the U.S. class C waste and all of the U.S. greater-than class C waste would be classified in France as low- and intermediate-level long-lived waste. The U.S. high-level waste would also be classified in France as high-level waste.)

3. The weight of the initial 1,000 metric tons of spent fuel in the figure includes only the weight of the fuel components and not the weight of the structural material used to contain the fuel pellets. The fuel components of the spent fuel are uranium, plutonium, minor actinides, and fission products—the sum of these components is equal to the weight of the uranium in the initial fuel. The weight of the structural material is included in the figure as part of the process waste resulting from reprocessing. Similarly, the weight of material shown in the figure considered by France to be reusable includes only the weight of the fuel components and not the weight of the structural material used to contain the fuel. In contrast, the weight of the radioactive material considered by France to be waste includes the weight of the radioactive material, including the weight of the fuel components, the structural material used to contain the fuel, and the storage containers. AREVA did not provide us with information on the weight

of the radioactive material in these containers separately from the weight of the containers.

4. The figure does not include radioactive materials that would be generated from the decontamination and decommissioning of reprocessing and recycling facilities nor the amounts of stored radioactive materials that have accumulated over the years from reprocessing and recycling.

5. AREVA and EdF noted that the reprocessing and recycling facilities and resulting radioactive materials are subject to, and meet, all safety, security, and environmental regulations.

Technical notes for the reprocessing and recycling process in France

[a]**Spent nuclear fuel:** France currently reprocesses and recycles all of the spent nuclear fuel it produces. It does not reprocess and recycle the spent MOX fuel and spent reprocessed uranium fuel coming out of this process.

[b]**Off-gases:** Reprocessing spent nuclear fuel generates gases that include the radioactive elements carbon-14, iodine-129, krypton-85, and tritium. Reprocessing 1,000 metric tons of spent nuclear fuel generates about 7.6 metric tons of volatile fission products that are released to the atmosphere as gases. Approximately 99.7 percent of these fission products are not radioactive. The other 0.3 percent of these fission products contains approximately 210,000 terabecquerels of radioactivity, primarily from the fission product krypton-85. (A terabecquerels is a trillion becquerels—a bequerel is a unit of measure of radioactivity.)

[c]**Water effluents:** Reprocessing spent nuclear fuel generates water effluents that include the radioactive elements carbon-14, iodine-129, and tritium. Reprocessing 1,000 metric tons of spent nuclear fuel generates about 0.3 metric tons of volatile fission products that are released to the sea. Approximately 77 percent of this material contains about 10,000 terabecquerels of radioactivity, primarily from iodine-129 and tritium.

[d]**Reprocessed uranium:** Reprocessed uranium contains some uranium isotopes, such as uranium-232 and uranium-236, and trace amounts of other radioactive elements, including plutonium, fission products, and minor actinides. AREVA did not provide information on the amount of this trace material.

[e]**MOX scrap:** This material consists of ceramic powder that is a byproduct of the fabrication process (e.g., grinding dust) and also of MOX fuel pellets that did not meet the needed technical or quality specifications—materials that are collectively referred to as MOX scrap. Of the approximately 12 metric tons of MOX scrap generated from reprocessing 1,000 metric tons of spent fuel, about 95 percent is of high enough quality that it is recycled at the fuel fabrication facility, while the remaining 5 percent is sent back for reuse at the reprocessing facility.

[f]**Reprocessed uranium fuel fabrication:** This facility only generates very low-level very short-lived radioactive material.

[g]**Reprocessed uranium fuel:** Reprocessed uranium fuel comprises 100 percent enriched reprocessed uranium.

[h]**MOX fuel:** MOX fuel compromises about 8.5 percent plutonium and 91.5 percent depleted uranium (depleted uranium is a byproduct of the initial enrichment of uranium).

[i]**Reactors loaded with reprocessed uranium fuel:** These are conventional nuclear reactors that do not require any modifications to use this fuel, and they can use up to 100 percent of this fuel for operation. Currently 4 of France's 58 nuclear reactors are licensed to use this fuel.

[j]**Reactors loaded with MOX fuel:** These are conventional nuclear reactors that require no or minor modifications to use this fuel and can use up to 30 percent of this fuel for operation; the remainder of the fuel is conventional enriched uranium fuel. Currently, 21 of France's 58 nuclear reactors are licensed to use MOX fuel.

Technical notes for the radioactive material generated from reprocessing and recycling in France

[a]**Vitrified high-level waste (HLW):** Reprocessing 1,000 metric tons of spent nuclear fuel generates 35 metric tons of HLW waste and 213 metric tons of packaging material, such as the glass in which the radioactive material is encased and the steel storage containers holding the vitrified HLW.

[b]**Process waste (HLW and intermediate-level waste, long-lived, (ILW-LL)):** This waste includes the cladding material, end-fittings, and other structural material used to contain the nuclear fuel pellets. This material is compacted and packaged into steel containers similar to those used to contain vitrified HLW. The weight of the material shown in the figure is the combined weight of the radioactive waste generated from

reprocessing and recycling and the weight of the container. AREVA did not provide separate information on the weight of the radioactive waste and of the container.

[c]**Technological waste (HLW and ILW-LL):** Technological waste consists of waste generated by plant operations (e.g., filters, pumps) contaminated with radioactive elements. This waste is compacted or cemented into different storage containers. The weight of the material shown in the figure is the combined weight of the radioactive waste generated from reprocessing and recycling and the weight of the container. AREVA provided the volume of this material but did not provide separate information on the weight of the radioactive waste and of the container.

[d]**Technological waste (low-level waste):** Technological waste typically consists of contaminated items, such as protective clothing, maintenance waste, and failed equipment. The weight of the material shown in the figure is the combined weight of the radioactive waste generated from reprocessing and recycling and the weight of the container. AREVA did not provide separate information on the weight of the radioactive waste and of the container.

[e]**Depleted reprocessed uranium:** Depleted reprocessed uranium is radioactive material generated by the reenrichment process. It contains trace amounts of other radioactive elements, including plutonium, fission products, and minor actinides from the reprocessed uranium that was reenriched. AREVA did not provide information on the amount of this trace material.

Appendix V: The United Kingdom Experience in Reprocessing and Recycling Spent Nuclear Fuel

According to United Kingdom government and nuclear energy officials and subject matter experts, the United Kingdom has decades of experience with reprocessing and recycling spent nuclear fuel. This appendix discusses (1) the United Kingdom's nuclear energy industry and the relevant oversight entities, and (2) the United Kingdom's reprocessing and recycling facilities and operating experiences.

Oversight of Nuclear Energy

According to United Kingdom documents, government officials, and subject matter experts, the United Kingdom's nuclear power infrastructure produces about 18 percent of the nation's electricity needs. This infrastructure includes facilities to reprocess and recycle spent nuclear fuel. The primary United Kingdom government agency involved in overseeing the nuclear power infrastructure and policy is the Department of Energy and Climate Change, which was created in 2008 to bring together energy policy and climate change mitigation policy.

Through the Energy Act of 2004 the government created the Nuclear Decommissioning Authority (NDA), a government-owned organization with responsibilities for decommissioning and cleaning up the facilities and waste from the United Kingdom's nuclear power infrastructure.[1] To support its operations, NDA uses revenues generated from the United Kingdom's reprocessing and recycling facilities—in Sellafield, Cumbria, in the northwestern part of England—and from its Magnox nuclear reactors.[2] NDA also funds research across the United Kingdom's nuclear complex in support of its mission. This includes funding of research at another government-owned organization, the National Nuclear Laboratory,[3] which conducts research and development on new reactors, the operations of

[1]NDA took over the cleanup and decommissioning liabilities and contracts for reprocessing of spent nuclear fuel and fuel manufacturing of British Nuclear Fuels plc. British Nuclear Fuels was formed in 1971 from the production arm of the United Kingdom's Atomic Energy Authority.

[2]Sellafield Ltd, under contract with the NDA, operates the reprocessing and recycling facilities. Sellafield Ltd, whose parent body is Nuclear Management Partners, comprises a U.S. company, URS; a United Kingdom company, Amec; and a French company, AREVA. Magnox Ltd, under contract with the NDA, operates the United Kingdom's Magnox reactors. Magnox Ltd is owned by a U.S. company, EnergySolutions, Inc.

[3]The National Nuclear Laboratory is a government-owned, commercially-operated, customer-funded nuclear technology services provider operating in six locations in the United Kingdom. The current contractor is a consortium of Serco, Battelle, and the University of Manchester.

nuclear reactors and reprocessing facilities, and decommissioning and environmental cleanup. In 2009, the French utility company, EdF, acquired British Energy and took over the operation of the United Kingdom's 14 advanced gas-cooled nuclear reactors (AGR) and a light-water reactor.

The future of nuclear power in the United Kingdom was outlined in a government white paper issued in January 2008.[4] The report concluded that it is in the public interest to allow nuclear utility companies the option to build new nuclear reactors. The report also concluded that these companies should proceed with the expectation that spent fuel from any new nuclear reactors will not be reprocessed. However, the government recognizes that it is up to the utility companies to decide, in consultation with the government, if it is commercially feasible to reprocess and recycle spent fuel because the companies are responsible for their share of the waste management costs.

Reprocessing and Recycling Facilities and Operating Experiences

According to documents we reviewed, government officials, and subject matter experts, the United Kingdom has decades of experience with reprocessing and recycling spent nuclear fuel. The discussion below describes the configuration and operating experiences of (1) three reprocessing facilities, (2) a uranium reenrichment facility, (3) four fuel fabrication facilities, and (4) reactors that use recycled nuclear fuel.

Reprocessing Facilities

The United Kingdom has had three reprocessing facilities at its Sellafield site. It built its first industrial-scale reprocessing facility after World War II to obtain plutonium for its weapons program, and this facility was decommissioned in the 1970s. It built its second—the Magnox reprocessing facility—in 1964 to reprocess spent nuclear fuel from its Magnox nuclear reactors.[5] Reprocessing this fuel was necessary because its magnesium alloy cladding proved chemically unstable in storage. The Magnox facility has a licensed capacity to process up to 1,500 metric tons of spent Magnox fuel annually. Over its lifetime, the Magnox facility has

[4]HM Government, *White Paper on Nuclear Power: Meeting the Energy Challenge* (London, England: Department for Business Enterprise & Regulatory Reform, January 2008).

[5]The United Kingdom had 26 Magnox reactors connected to the electricity grid by 1971. Of these, 22 are shut down and are in various stages of decommissioning, and 4 continue to operate.

reprocessed more than 44,000 metric tons of spent Magnox fuel and returned over 15,000 metric tons of uranium to the fuel cycle. The facility is expected to operate until 2016 to complete reprocessing the spent fuel generated by the four remaining Magnox reactors. NDA expects to shut down these reactors in 2012.

The third reprocessing facility—the Thermal Oxide Reprocessing Plant (THORP)—was approved for construction in 1978 and began operations in 1994. This facility was initially intended to (1) capitalize on the projected worldwide expansion of nuclear power and the expected demand for reprocessing spent fuel services from nuclear utilities in other countries and (2) reprocess spent nuclear fuel from the country's 14 AGRs to provide plutonium for the fleet of fast reactors that was expected to be constructed in the United Kingdom.[6] It initially had a licensed capacity to process up to 1,200 metric tons of spent nuclear fuel annually. According to NDA documents, the construction costs for THORP were paid for by domestic utility companies, as well as nuclear utilities in other countries that needed to reprocess their spent nuclear fuel but did not have the facilities to do so. Also according to NDA documents, as of 2010, THORP had reprocessed about 6,000 metric tons of spent nuclear fuel—about 60 percent, or about 3,700 tons, from nuclear utilities in other countries, primarily Germany and Japan. THORP is expected to operate until 2018, when it plans to complete its current reprocessing contracts for the remaining approximately 500 metric tons of spent nuclear fuel that still needs reprocessing for nuclear utilities in other countries and about 2,500 metric tons of spent fuel from the United Kingdom's AGRs. The last AGR is expected to shut down in 2023, but its utility owner, EdF, may decide to seek a license extension to continue operating some AGRs beyond this date. NDA officials explained that any AGR spent nuclear fuel that is not reprocessed after THORP closes will be put into long-term storage pending a decision on its disposal.

THORP has never achieved its licensed capacity because of changes in market demand for reprocessing services and technical problems. According to a subject matter expert in the United Kingdom, about the time that THORP began operations, the original rationale for the facility—providing reprocessing services and using plutonium for fast reactor

[6]The United Kingdom operates one light-water reactor but does not reprocess the spent nuclear fuel; instead, it stores the spent fuel pending disposal in a planned geologic repository.

programs—had diminished.[7] For example, Germany had contracted to reprocess a total of 1,500 metric tons of spent nuclear fuel but reduced this amount by 550 metric tons within months of THORP's opening. Furthermore, according to subject matter experts, THORP's technical problems—including equipment failures and accidents involving acid spills, pipe leaks, and blockages—reduced its capacity for reprocessing. Most significantly, THORP was shut down for 3 years beginning in 2005 because of a pipe fracture in a critical portion of the facility. When THORP restarted operations in 2008, it could no longer operate at capacity because of the technical problems, and its capacity was downgraded to 600 metric tons per year. According to NDA officials, NDA has decided not to invest in THORP to restore operating capacity to its licensed capacity because of the high cost involved.

Uranium Reenrichment Facility

The United Kingdom reenriched the uranium generated from the reprocessing of spent fuel from its Magnox reactors and used the resulting fuel (reenriched reprocessed uranium fuel) in its AGR reactors up until about 2004. Reenrichment was conducted by Urenco, at its facilities in Capenhurst, in the northwestern part of England.[8] According to an NDA official, this facility reenriched about 16,000 to 20,000 metric tons of reprocessed uranium. This official explained that this reenrichment began in the 1980s and ended in 2004 because the low price of uranium made reenriching reprocessed uranium uneconomic.

Fuel Fabrication Facilities

The United Kingdom operates or has operated four facilities for fabricating fuel out of the uranium and plutonium produced by reprocessing. The following describes their operations:

- The Springfields Works facility, owned and operated by Westinghouse, located in Preston, England, fabricated reprocessed uranium fuel for AGR reactors until 2004. According to an NDA official, this facility produced about 1,000 to 1,650 metric tons of reprocessed uranium fuel.

[7] Forwood, Martin, "The Legacy of Reprocessing in the United Kingdom, research report of the International Panel on Fissile Materials" (Princeton, New Jersey: July 2008).

[8] Urenco is jointly owned by the United Kingdom, the Netherlands, and two German utilities.

- Between 1963 and 1988, British Nuclear Fuels operated a MOX fuel fabrication facility at Sellafield that produced about 20 metric tons of MOX fuel from plutonium and depleted uranium. According to an NDA official, this MOX fuel was used in the United Kingdom's fast reactors.

- Between 1993 and 1999, the MOX Demonstration Facility—a small-scale plant to prove the technology to produce MOX fuel—operated at Sellafield. This facility had a licensed capacity to produce up to 8 metric tons of MOX fuel annually for nuclear utilities in Germany, Japan, and Switzerland; however, it produced only 16 metric tons of MOX fuel during its 6 years of operations. NDA officials attributed this low output to significant operational delays. For example, operations were shut down because quality assurance data that accompanied a MOX fuel shipment to Japanese nuclear utilities were found to be falsified, making the fuel unacceptable, and the shipment was returned to the United Kingdom.

- In 2001, the Sellafield MOX Facility began operations to fabricate MOX fuel for nuclear utilities in other countries, primarily Japan. The Sellafield MOX Facility is licensed to produce up to 120 metric tons of MOX fuel annually; it first exported MOX fuel in 2005. However, according to subject matter experts, this facility encountered technical problems when it first began operations, including equipment breakdowns that reduced its output. In 2005, the facility's capacity was downgraded to up to 40 metric tons per year. According to a United Kingdom report, in 9 years of operation, this facility produced 15 metric tons of MOX fuel—a small fraction of its original target of 560 metric tons over an expected 10 years of operating life.[9] Starting in 2008, NDA subcontracted fabrication of some MOX fuel to AREVA's Melox facility to complete its current contracts with nuclear utilities in Japan. In August 2011, NDA announced that it would close the facility as a result of the potential delays in orders for MOX fuel from utilities in Japan following the earthquake in Japan and subsequent events.

[9]United Kingdom Department of Energy and Climate Change, *Management of the UK's Plutonium Stocks: A consultation on the long-term management of UK owned separated civil plutonium* (London, England: February 2011).

Reactors Using Recycled Fuel

The United Kingdom has made only limited use of reactors using nuclear fuels that rely on the uranium and plutonium resulting from reprocessing, as the following describes:

- The United Kingdom had initially intended to recycle the plutonium derived from reprocessing Magnox and AGR spent nuclear fuel in its fast reactor program. The United Kingdom operated two fast reactors: the 14 megawatt (MW) Dounreay fast reactor operated between 1959 and 1977, and the 250 MW prototype fast reactor operated from 1974 through 1994. These reactors were used to test various materials and nuclear fuels, including fuels fabricated from uranium and plutonium from reprocessing. However, the United Kingdom decided to abandon its fast reactor program in 1994. There were a number of factors behind this decision, according to an NDA official. These factors included low uranium and natural gas prices for power generation and reduced interest in nuclear energy following the 1986 Chernobyl accident. In addition, fast reactor technology proved more difficult to commercialize than at first anticipated.

- The United Kingdom had used reenriched reprocessed uranium fuel in its AGRs until 2004 when the low price of uranium made reenriching reprocessed uranium fuel uneconomic.

- According to NDA officials, aside from the use of MOX fuel in fast reactors, the United Kingdom has never used MOX fuel in any of its other reactors. According to these officials, the government has not ruled out the use of MOX fuel in planned nuclear reactors. In 2008, the United Kingdom decided to support the building of new nuclear power reactors, and nuclear utility companies, including EdF, have come forward with plans to build at least nine new reactors. According to EdF officials we spoke to in France, these reactors will be designed to use up to 50 percent MOX fuel. According to an NDA official, nuclear utilities have an option to come forward with plans to reprocess spent nuclear fuel from any new reactors and to use MOX fuel, but no utility company has come forward with plans to do so.

Appendix VI: Comments from the Department of Energy and GAO's Response

Note: GAO comments supplementing those in the report text appear at the end of the appendix. (Page references in the letter may differ.)

Department of Energy
Washington, DC 20585

SEP 2 1 2011

Mr. Gene Aloise
Director, Natural Resources
and Environment
U.S. Government Accountability Office
441 G Street, NW
Washington, D.C. 20548

Dear Mr. Aloise:

Thank you for providing a draft copy of the Government Accountability Office (GAO) report, "Nuclear Fuel Cycle Options: DOE Needs to Enhance Planning for Technology Assessment and Collaboration with Industry and Other Countries," (GAO-11-512). We appreciate your thorough review as evidenced by the summary of your activities in Appendix I. We are also pleased that you've acknowledged our systematic approach to planning for the complex scientifically challenging process that lies ahead.

The draft report recommends that we revise our R&D plans to:

- Include the current readiness levels of the technologies associated with the fuel cycle options being considered and the estimated time and cost for developing these technologies in relationship to the R&D plan's schedules and goals,
- Include a strategy for sustaining long-term collaboration with the role industry will have at critical points in selecting fuel cycle options and associated technologies, and
- Specify how DOE will use collaborative agreements with other countries to advance its R&D efforts and use available facilities and expertise in these other countries to more efficiently and effectively meet its R&D goals.

The draft report also recommends that we complete a memorandum of understanding with NNSA to help ensure that DOE's Office of Nuclear Energy and NNSA coordinate their work to avoid overlap and duplication in their efforts to minimize proliferation and terrorism risks.

We agree that technology assessments and collaboration with industry and other countries are important elements of the Fuel Cycle Research and Development program and must be planned well for the program to succeed. We will continue to refine our planning efforts beyond the Nuclear Energy Research and Development Roadmap and implementation plans that your office reviewed. As we do, we will develop more detailed plans regarding those elements.

Below are more specific comments on each of the major recommendations in the draft report followed by the clarification of certain factual representations.

1. Technology Readiness Levels

Technology maturity was assessed as one of ten criteria as part of the initial screening of fuel cycle options conducted in FY 2010. This initial screening was a pilot application of a formal evaluation process. For the initial screening, a qualitative assessment was made of the maturity of fuel cycle systems and its components. Lessons learned from its use will be applied to a follow-on screening planned for FY 2013. While not yet finalized, one of the areas identified for improvement is to modify the performance metrics for technology maturity with an estimate of the cost and time to develop a technology to a readiness level suitable for transfer to industry.

However, at this stage we are evaluating large numbers of fuel cycle systems and are not performing detailed evaluation of the readiness of specific technologies. As we progressively narrow the focus of the systems that merit attention, greater attention will be placed on defining the technology readiness and the costs and time to improve that readiness for specific candidate technologies. Technology readiness information developed and evaluated as part of the FY 2013 and follow on screening processes will be incorporated into revisions to our research and development plans.

2. Industry Collaborations

Collaboration with industry is seen as a vital component of the program. Indeed, we recognize that industry is the ultimate user of the technologies developed by the program. Toward that end, the program has engaged industry via multi-year advice and assistance contracts that allow them to attend meetings and respond to tasks and requests of the program as we shape and conduct our R&D. For example, the industry teams provided significant feedback on the initial screening of fuel cycle options conducted in FY 2010, including helping to define options to be evaluated, performance metrics, as well as reviewing the results of the evaluations. It is intended that industry participate in a similar manner in future planned screenings as we progressively narrow the number of options that are considered for research and development.

Once sufficient research has been conducted to warrant large-scale demonstration, industry will need to be engaged through partnerships to conduct the demonstrations. The program will clarify its intention vis-à-vis industry engagement over the long-term as part of revisions to its R&D plans.

3. International Collaborations

DOE has had decade-long relationships with several countries through international collaborations. These international collaborations have yielded mutual benefit for all parties involved through various R&D activities. An example of such collaboration is DOE's Action Plans. Currently, DOE has Action Plans with China, Japan and Russia.

Action Plans are vehicles that allow both countries to undertake R&D activities more efficiently by collaborating in key facilities and technologies unique to each party. The U.S.-Japan Joint Nuclear Energy Action Plan was signed in April 2007. The U.S.-China Bilateral Civil Nuclear Energy Cooperative Action Plan was signed in September 2007. The U.S - Russia Civil Nuclear Energy Cooperation Action Plan was signed in March 2010. Examples of action plan R&D areas and working groups include the following: fast reactor technology, advanced separations technology (including waste forms), advanced fuels and related materials, safeguards and physical protection technologies and modeling and simulation.

All DOE R&D activities are evaluated and revisited regularly and modified as necessary through the budget process to ensure that the portfolio reflects past progress, current priorities, and future opportunities for international collaboration.

The Nuclear Energy R&D Roadmap does not provide details regarding approaches for how international collaborations will advance DOE's R&D efforts, but these details are available in other documents. For example, the U.S. – Russia Civil Nuclear Energy Action Plan identifies irradiation testing of advanced and innovative fuels and materials in Russian test reactors as one of the areas of collaboration. In implementing the action plan, specific approaches for accomplishing these irradiations have been developed and documented in workshop reports. As these types of efforts mature and funding requirements are identified, the potential impact on the need for domestic nuclear research facilities can be formally assessed.

With respect to IFNEC contributions to advancing nonproliferation goals through international collaborations, in addition to supporting U.S. policy objectives through engagement at meetings and development of topical white papers, examples include: (1) development of a tool (through NE and NA collaboration) to help countries effectively plan for needed human resource development (including resources required for nuclear safeguards) and transfer of this tool to the IAEA for broader access and (2) providing attention and focus on the important contributions that nuclear fuel services can provide through identifying broad interests, key challenges, and approaches that can be taken multilaterally to enable progress.

4. Cooperation between the Office of Nuclear Energy and the National Nuclear Security Administration

Formal interactions at the highest levels between NE and NNSA occur on a monthly basis between the Assistant Secretary for the Office of Nuclear Energy and the Deputy Administrator for Defense Nuclear Nonproliferation. Additionally, coordination occurs on a more frequent and regular basis between the different offices with respect to ongoing programmatic initiatives and activities. This includes reviews of R&D plans, the NE R&D Objective 4 Implementation Plan, attendance at workshops, and interaction of technical staff. Additionally, there is formal NE-NNSA coordination, for example, that comprises the 10 CFR Part 810 review process, which has important nonproliferation implications. While NE and NNSA initially considered an MOU to formalize coordination, the existing efforts have promoted significant teamwork. The Nuclear Energy R&D Roadmap and the Objective 4 Implementation Plan underscore the importance of coordination between NE and NNSA and these efforts will continue to be supported with approaches documented in planning documents, as they are updated and refined.

Clarification of Facts

See comment 1.

1. In the first bullet on the highlights page describing the screening process, the 863 nuclear fuel cycles were grouped into 266 for further exploration. They were not reduced to 266. Page 16 of the draft report describes this process more accurately.

See comment 2.

2. Footnote 3 on page 2 should be deleted. It is not necessary for the point made in the body of the report and is not accurate as written. DOE has the responsibility to dispose of spent nuclear fuel and high-level radioactive waste but is not required under the NWPA to build and operate a repository.

See comment 3.

3. The last sentence of the first paragraph under the heading Nuclear Fuel Cycles on page 9 should be deleted because it is inaccurate. There is not a current U.S. policy to dispose of spent nuclear fuel and high-level radioactive waste in a geologic repository.

See comment 4.

4. The statement on page 2 of the draft report states that "[o]ther countries, such as France, rely on a closed fuel cycle to manage their spent nuclear fuel" is misleading. While it is true that once-through is the current approach in the U.S. and a closed fuel cycle is being pursued by other countries, none of these fuel cycles are actually being used. Until used nuclear fuel is permanently disposed, the U.S. is not actually using a once-through fuel cycle. Similarly, until methods for repeated recycle are matured and implemented with the employment of fast reactors, the closed fuel cycle is not actually being used or relied on.

See comment 5.

5. Page 10 of the draft report describes the modified open fuel cycle as "using limited or no reprocessing or recycling". As stated in the DOE R&D Plan, the modified open cycle always includes limited separation steps.

See comment 6.

6. Page 23, footnote #23, of the draft report provides misleading difference between fast reactors and thermal reactors. The fission process is the same in both fast and thermal reactors, so the neutrons produced have the same fast energy level. The difference is thermal reactors use a moderator material to deliberately slow the neutrons to thermal energy levels, increasing their interaction with the fuel material. Fast reactors do not include this moderator material, and fast neutrons are more likely to collide with fuel isotopes instead of interacting to create a fission event or a neutron capture event. For this reason, fast reactors typically require higher fuel enrichment to maintain a reaction, and are being developed because they are more capable in transmuting certain long-lived and more hazardous isotopes to shorter lived or less hazardous isotopes.

See comment 7.

7. Page 23, footnote #24, of the draft report provides misleading characterization of IFNEC as "a partnership of countries aiming to improve the proliferation resistance of the nuclear fuel cycle while guaranteeing access to fuel supplies." IFNEC has a broader aim as an international forum of 29 member countries, 30 observer countries, and 3 observer organizations, created to explore mutually beneficial approaches to ensure the use of nuclear energy for peaceful purposes proceeds in a manner that is efficient and meets high standards of safety, security and non-proliferation.

See comment 8.

8. Page 24 of the draft report discusses I-NERI collaborations and then references agreements with multiple countries. The only active I-NERI agreements are with ROK, France, Euratom, and Canada.

See comment 9.

9. Page 27 of the draft report misstates the focus of DOE efforts to minimize proliferation and terrorism risks associated with nuclear fuel cycles ("In accordance with its R&D plan, DOE has three efforts under way to understand and: (1) developing and validating a methodology to assess these risks, (2) safeguarding nuclear material, and (3) participation in IFNEC to advance U.S. interests in minimizing these risks"). The R&D Objective 4 Implementation Plan describes four areas: development of intrinsic design features for minimizing proliferation and terrorism risks; development of next-generation materials protection, accounting and control; support for the development of international frameworks and institutions; and advancing the state of the art for proliferation and terrorism risk assessment to contribute to risk-informed nuclear energy R&D plans and priorities.

See comment 10.

10. Page 30 of the draft report limits the description of the comprehensive nuclear fuel services. The description of comprehensive nuclear fuel services should be broadened, as follows, so that it is more consistent with current usage: Comprehensive Nuclear Fuel Services (CFS) is an approach in which commercially-based nuclear fuel cycle services-- including fuel leasing, regional or internationally-managed interim storage, and disposition of used fuel with the supplier or a third party--are made available on a global basis to countries meeting their nonproliferation responsibilities. The term "comprehensive" indicates that services may span the entire fuel cycle, but the flexible and tailored nature of CFS should accommodate solutions unique to each customer.

Sincerely,

R. Shane Johnson
Principal Deputy Assistant Secretary
for Nuclear Energy

The following are GAO's comments to the Department of Energy's letter dated September 21, 2011.

GAO Comments

1. We modified the report.

2. We deleted the footnote.

3. We deleted the sentence.

4. We did not modify the statement. As our report notes, the difference between a once-through, or open fuel cycle and a closed fuel cycle is whether the spent fuel is reused. The United States has not reused spent fuel; hence we consider the U.S. fuel cycle as once-through, or open. Because France reuses spent fuel, we consider its system a closed fuel cycle.

5. We used the language in DOE's implementation plan for the roadmap to describe the modified open fuel cycle. The implementation plan was issued 9 months after the roadmap, and the implementation plan was to elaborate on the information in the roadmap. We suggest that DOE reconcile the differences in these two documents in explaining the modified open fuel cycle.

6. We revised this footnote. The revised footnote uses the definition of a fast reactor from DOE's *Draft Global Nuclear Energy Partnership Programmatic Environmental Impact Statement*, DOE/EIS-0396 (Washington, D.C.: Office of Nuclear Energy, October 2008).

7. See comment 1.

8. See comment 1.

9. We added a footnote to clarify that we had consolidated objectives one and two into a general objective of safeguarding nuclear material.

10. See comment 1.

Appendix VII: GAO Contact and Staff Acknowledgments

GAO Contact

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Staff Acknowledgments

In addition to the individual named above, Daniel Feehan, Assistant Director; Cristian Ion; Anne Rhodes-Kline; Thomas Laetz; Armetha Liles; Timothy Persons; Katherine Raheb; Carol Herrnstadt Shulman; Kiki Theodoropoulos; and Rajneesh Verma made key contributions to this report.

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