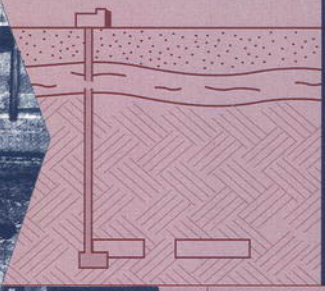
END POINTS

for Spent Nuclear Fuel and High-Level Radioactive Waste in Russia and the United States



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End Points for Spent Nuclear Fuel and High-Level Radioactive Waste in Russia and the United States

Committee on End Points for Spent Nuclear Fuel and High-Level Radioactive Waste in Russia and the United States

Board on Radioactive Waste Management

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COVER: Depicted are high-level radioactive waste at the bottom of an underground tank (upper left), an artist's rendition of a high-level waste repository (upper right), a nuclear fuel assembly being lowered into the core of a power reactor (lower left), and a spent fuel dry-storage facility (lower right). The first appears courtesy of the U.S. Department of Energy; the last two are courtesy of the Nuclear Energy Institute.

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Preface

Highly radioactive wastes in the United States and Russia are by-products of three interrelated programs that were born and grew rapidly during and after World War II: development and production of nuclear weapons, development and production of nuclear power, and the nuclear research that supported these activities. The character and diversity of the wastes produced within these programs pose difficult challenges to scientists, engineers, social scientists, and politicians who seek lasting and reliable strategies for managing these wastes.

Efforts now are being made by the Russian and the United States governments to identify appropriate interim and final "end points" for high-level wastes, either through interim storage in surface or near-surface facilities or through permanent disposal in deep geologic repositories. Disposal of high-level waste is a federal responsibility in both countries. The actual approaches to management of spent nuclear fuel and high-level waste in Russia and the United States are similar, although there is a philosophical difference in the desired approaches. Therefore, the programs share enough challenges and goals that there are many opportunities to collaborate and learn from each other. Further, the details of the current approaches should not be taken as fixed. Managerial decisions could and should be periodically revisited, taking into consideration technological progress and changes in the perception and understanding of the problem.

This report, the first on this topic prepared as a joint effort of Russian and American experts, describes quantities and locations of spent nuclear fuel and high-level waste in Russia and in the United States, as well as plans for managing and disposing of these wastes, and provides a technical assessment of interim and final end points being considered. The committee focused this study more on assessing technical factors rather than on evaluating government policy. Funds, schedules, and other constraints did not permit the committee to do a comprehensive review, to visit many sites, or to analyze the risks and costs associated with various possible decisions. The committee instead relied on the expertise of its individual members, each of whom is familiar with some of the relevant sites, facilities, and problems. Committee staff provided background information on inventories and sites in the United States. The committee also commissioned papers, writ-

ten by scientists and engineers at institutes and facilities in Russia, covering topic areas, such as radiochemical separations and fuel fabrication, and inventories and practices at the Russian sites. Russia's Pacific Fleet and the Siberian Chemical Combine at Tomsk, however, were not covered in any detail. The technical background papers, which have been placed in the National Academies public access file (available via its Public Access Records Office, http://www4.nationalacademies.org/onpi/paro.nsf/), provided much of the data and background text found in the committee's report. They do not, however, represent a consensus of the committee. Analyses, conclusions, and recommendations in the technical background papers are those of the listed authors, whereas the committee's conclusions and recommendations can be found in the body of this, the committee's report.

The committee's report builds on work done in previous studies by the U.S. National Research Council (NRC),[1] described in reports entitled Proliferation Concerns: Assessing U.S. Efforts to Help Contain Nuclear and Other Dangerous Materials and Technologies in the Former Soviet Union (1997), Protecting Nuclear Weapons Material in Russia (1999a), Disposition of High-Level Waste and Spent Nuclear Fuel: The Continuing Societal and Technical Challenges (2001a), and other reports by the NRC (see http://www.nas.edu/brwm/reports.html). A few comprehensive English-language descriptions of radioactive waste and the nuclear fuel cycle in the Former Soviet Union are currently available (see, for example, Bradley [1997]). This new study utilized the information contained in the commissioned papers, which can be seen as a continuation of the compilations begun by Bradley and others.

Some issues associated with management of radioactive waste have changed very little in recent decades: for example, essentially the same storage technologies are available, although some are becoming more widespread. Other issues are undergoing rapid change and events that have occurred during the course of this study illustrate that point. The Russian Federation has passed laws allowing for importation of spent nuclear fuel from other nations. The United States has decided to pursue a license application for a deep-geologic repository at Yucca Mountain for disposal of spent nuclear fuel and high-level radioactive waste. And the terrorist acts in the United States on September 11, 2001, along with proclamations by terrorist organizations that they intend to acquire and make use of nuclear materials for terrorist acts,

[1] The National Research Council is the chief operating arm of the National Academies in the United States.

underscore the need for countries possessing such materials to undertake appropriate efforts to prevent their intentional misuse (see, e.g., NRC [2002]). Russia and the United States have the largest inventories of these materials and have both been targeted by terrorists. Analyzing the end points in management of spent nuclear fuel and high-level radioactive waste is a step in reducing vulnerabilities to, and mitigating the consequences of, such acts.

The hazards from spent nuclear fuel and high-level radioactive waste will endure over time spans far longer than the recorded history of either Russia or the United States. Over the same period of recorded history, distances that once were nearly insurmountable now are readily traversed in less than a day. This underscores the increasing connectedness of our world. Dealing with wastes and environmental hazards responsibly is increasingly an international or global responsibility. Russia and the United States are responsible for generating the largest amounts of spent nuclear fuel and high-level radioactive waste. It is correct and fitting that they act together in trying to define the problems and to propose plans of action to address the problems.

In this, the seventh decade of the nuclear age, the Russian and U.S. governments are making important efforts in formulating and implementing technically robust and societally responsible visions for managing the back end of the nuclear fuel cycle, waste management. These efforts, if successful, can serve as guides to promote the safe, secure, and environmentally sound management of spent nuclear fuel and high-level radioactive waste worldwide. Achieving technically sound and politically sustainable progress, however, will require the continued cooperation among the international scientific, engineering, and policy-making communities, especially to promote technical information exchange and to develop and disseminate best practices. It is in this spirit, then, that the committee presents this report to the Russian and U.S. governments in the hope that it will help promote continued cooperation that will benefit both countries and the world community at large.

John F. Ahearne and Nikolai P. Laverov

Co-chairmen, Committee on End Points for Spent Nuclear Fuel and High-Level Radioactive Waste in Russia and the United States

Acknowledgments

This study was undertaken with the cooperation of the Russian Academy of Sciences. The Russian Academy of Sciences is the Russian Federation's premier scholarly scientific institution. The Academy's main responsibilities are pursuit of fundamental research into natural and social sciences, and promotion of the practical application of science. Established by Peter the Great and a Senate decree in 1724, the Academy is a self-governing organization constituted in part by a network of research institutes and laboratories, and serves as the chief scientific and technological adviser for the government. Academician Yury Osipov is president of the Russian Academy of Sciences.

Many people within and outside of the academies in Russia and the United States helped make this study possible. The Ministry of Atomic Energy of the Russian Federation and the U.S. Department of Energy provided information, presentations, and access to facilities. Dr. Yuri K. Shiyan of the Russian Academy of Sciences helped in many ways, at times serving as interpreter and as coordinator of the meeting in Moscow, and generally assisting the co-chairmen throughout the study. Ms. Angela Taylor and Ms. Chelsea Sharber of the National Academies coordinated the meeting in Washington and all of the committee travel, and Ms. Latricia Bailey readied the English manuscript for publication. Professor Vassily I.Velichkin, Professor Alexander A. Pek (as committee member, translator, and more) of IGEM in the Russian Academy of Sciences, and Dr. Micah Lowenthal of the National Academies helped to develop this report, and BRWM staff director Dr. Kevin Crowley and OCEE staff director Mr. Glenn Schweitzer guided the project from its initiation to its completion.

List of Reviewers

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

Leonid A. Bolshov, Institute of Nuclear Safety, Russian Academy of Sciences
Don J. Bradley, Pacific Northwest National Laboratory
Thomas B. Cochran, Natural Resources Defense Council
Sergey A. Dmitriev, “Radon” Scientific & Industrial Association
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Jane C. S. Long, Mackay School of Mines
Ernest J. Moniz, Massachusetts Institute of Technology
Frank L. Parker, Vanderbilt University
Ashot A. Sarkisov, Institute of Nuclear Safety, Russian Academy of Sciences

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Harold K. Forsen, foreign secretary of the National Academy of Engineering. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

This study, requested by the U.S. Department of Energy (DOE), provides a scientific and technical analysis of the management of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) in Russia and the United States and describes inventories, compares the approaches taken in the two countries, and assesses the end-point options for interim and long-term storage of materials and wastes and for permanent disposal of wastes. An end point for spent nuclear fuel or high-level radioactive waste is a stable, safe, and secure disposition of the material that can be sustained.

The activities of managing SNF and HLW in the two countries are now similar in many respects. In the United States, the majority of SNF is in storage and is likely to remain so for at least two decades. In Russia, while most of the commercial SNF at present also is being stored, a limited portion undergoes chemical processing. At the same time, both countries chemically process liquid HLW in order to immobilize it for safer storage and disposal.

The United States and Russia, however, have different approaches to and long-term strategies for realizing end points for SNF and HLW. The United States currently plans to transport SNF to a geologic repository for disposal without chemical processing. Russia plans to develop the capacity to chemically process all of its SNF (with the possible exception of SNF from RBMK reactors) to recover and reuse uranium and plutonium in reactors, while immobilizing the HLW from the processing, and disposing of the immobilized waste in geologic repositories at the processing sites. Each approach has its advantages and disadvantages.

Selection of end points and approaches to end points can be informed by science and engineering, but the selection involves policy decisions that incorporate economics, political considerations, and, in some cases, international relations. Decisions

must address both interim short-term endpoints and final long-term end points. In doing so, safety, environmental impact, and proliferation concerns must be included.

ASSESSMENT OF END POINTS

Technologies exist for safe, secure, and sustainable storage of most SNF. These technologies are likely to be effective for several decades of storage and can be deployed in a range of locations and circumstances. Storage of liquid HLW over long periods of time is less reliable, and immobilization of liquid HLW into a form that can be safely, securely, and sustainably stored is preferable.

Geologic disposition has been considered the most promising option for disposal of high-level radioactive waste since at least 1957, when a report of the National Research Council concluded that “wastes may be disposed of safely at many sites,” suggested that “disposal in cavities mined in salt beds and salt domes” promises “the most practical immediate solution of the problem,” and noted that solidifying the waste into an insoluble form would simplify disposal (NRC 1957). A recent report by an international committee of the National Research Council concludes that geologic disposition is the only long-term end point that does not require continued management and resource expenditure (NRC 2001a). Worldwide, no engineered geologic repository for HLW has been designed and operated as yet, although the Waste Isolation Pilot Plant (WIPP) in the United States is an operating geologic repository for long-lived transuranic waste.

These interim and final end points are necessary parts of any nuclear fuel cycle. At the same time that these end points are being implemented, improved, and developed, other actions are needed to support their effective deployment as part of Russia and the United States’ preferred fuel cycles.

OVERALL ASSESSMENT OF PROBLEMS AND PROGRESS

Russia and the United States face many similar problems in managing SNF and HLW, but Russia is in a different stage of addressing its problems than is the United States. In both countries progress is being made in managing the radioactive waste problems, but the progress is slow and the hazard of radiation

events grows both in Russia (e.g., continuing accumulation of liquid HLW at SNF reprocessing plants, degraded SNF in disabled service ships and existing ground storage facilities) and in the United States (e.g., leaking and aging underground HLW tanks).

The U.S. Department of Energy (DOE) already has addressed its most pressing HLW problems that pose immediate risks to workers and the public, although some problems still require attention because the measures taken have been temporary solutions. The Ministry of Atomic Energy of the Russia Federation (Minatom) has made efforts to address the most serious environmental and waste-management problems within its nuclear complex, and has made progress on some of them. But the resources available for these activities in Russia have been much smaller, and some of the problems, particularly the environmental contamination, are more difficult and urgent than their counterparts in the United States. As a result, the timeframe for dealing with the problems requiring near-term actions in Russia is more immediate than in the United States.

Over the next few decades, both countries also must address the development of interim and final end points, including any necessary research and development.

ASSESSMENT OF NEAR-TERM ACTIONS NEEDED IN RUSSIA

In Russia, progress is being made as HLW at the Production Association “Mayak” (PA “Mayak”) is immobilized in aluminophosphate glass logs and stored onsite; storage facilities are planned for SNF at several sites; and the rate of defueling of decommissioned nuclear-powered submarines has increased. It is the committee’s judgment that the following recommendations require action in timeframes of months or years.

Protect HEU and Plutonium and Immobilize HLW

Because of the potentially horrible consequences of theft of nuclear materials containing highly enriched uranium (HEU) and plutonium, efforts to prevent such thefts should be strengthened. This can be accomplished by improving materials protection, control, and accounting (MPC&A) at sites where HEU (including HEU SNF) and plutonium are stored and by consolidation of these materials in well-protected, centralized storage facilities. Accelerating

completion of the specialized plutonium storage facility at PA "Mayak" would facilitate these efforts.

Because liquid HLW and SNF present both potential targets for terrorist attacks and potential material for manufacturing radiological weapons ("dirty bombs"), all SNF should be provided immediately with proper physical protection. Likewise, there should be constant monitoring of storage sites for intense radiation sources, and programs to immobilize liquid HLW should be accelerated.

Stabilize Unretrievable Fuel Stored in Floating Technical Bases and Unload Retrievable Fuel from Decommissioned Nuclear Submarines

The state of the Russian nuclear fleet's floating technical bases with stored SNF is generally poor, meaning that the ships are disabled and, therefore, it is sometimes acutely dangerous to continue to store SNF in them. The condition of the fuel in these ships should be stabilized, and plans should be made to remove it. Dozens of decommissioned nuclear submarines are moored in bays and await defueling. As soon as possible, their fuel should be unloaded and shipped to secure storage sites at PA "Mayak," or properly stored in specialized facilities on shore, which would need to be constructed.

Discontinue Dumping of Liquid Radioactive Wastes at PA "Mayak"

Liquid radioactive wastes continue to be dumped into Lake Karachai and the Techa Ponds Cascade at the PA "Mayak." This leads to serious risks of further environmental pollution, including underground and surface-water contamination. Moreover, there is a threat of dam failure, which could result in contamination of the Techa water basin with water bearing radioactive waste. In order to reduce on-going contamination and to prevent accidents, the practice of dumping liquid radioactive wastes into Lake Karachai should be discontinued in the future and appropriate actions should be taken to decrease the water level in the Techa Ponds Cascade.

ASSESSMENT OF LONGER-TERM ACTIONS NEEDED IN RUSSIA

In addition to the near-term actions listed above, the committee concluded that the following longer-term actions are needed in Russia.

Study Isolation of Waste Injected into Deep Horizons

Deep-well injection disposal is used for large amounts of low- and intermediate-level waste generated by the radiochemical facilities at Krasnoyarsk, Tomsk, and Dmitrovgrad. According to previous investigations, injection of such wastes into deep, hydraulically isolated aquifers is likely to be safe. Many in the United States and Europe, however, remain skeptical about the practice of deep injection and believe that it should not continue. Given such disagreements, international teams should continue to study the issue. Meanwhile, as it exhausts the capacity of the existing wells, Russia should continue and enhance environmental monitoring to support more comprehensive study of the problem.

Improve Operations and Pursue End Points for SNF in Northwest Russia

With its nuclear submarines, the northwestern region of Russia has the highest concentration of nuclear powered facilities in the world. A large quantity of SNF has accumulated in the region, both from nuclear powered submarines (NPSs) and from the Kola and Leningrad nuclear power stations. Defueled reactor compartments from decommissioned nuclear-powered ships also have been stored in the region for long periods, floating moored in bays along the Kola Peninsula. At the same time, storage facilities built mostly in the 1960s to store SNF and radioactive waste are in an unsatisfactory state. So, in addition to the urgent need to deal with problems with the poor condition existing floating technical bases, work is needed to improve and introduce safe techniques and facilities for SNF unloading from floating NPS; develop safe techniques for management and final disposal of reactor compartments from decommissioned nuclear-powered ships; and build a regional facility for radioactive waste storage and a centralized storage facility for long-term storage of unreprocessible SNF.

Develop Long-Term SNF Storage Capacity in Russia

The available capacity for reprocessing of SNF in Russia is insufficient to match the rate at which the SNF is generated, so the inventory of SNF is growing. This implies that long-term storage will be needed. Russia should increase its capacity for long-term storage of SNF. In particular, interim dry storage for RBMK SNF at the reactor sites and centralized dry storage for VVER-1000 and RBMK SNF at the Krasnoyarsk Mining and Chemical Combine (MCC) should be developed and deployed to prevent overcrowding of SNF pools.

Further Develop MOX-Fuel Fabrication Technology

Russia plans to use MOX fuel in its thermal and fast reactors. Russia's VVER-1000 reactors are likely to be the first of Russia's thermal reactors to be loaded with MOX fuel. For this to be realized, further development of MOX-fuel-production technology, including fabrication of press powder with highly homogeneous plutonium distribution, is needed. At the same time, MOX fuel based on both weapon-grade and regenerated from VVER-440 SNF plutonium types has been already tested successfully in fast breeder reactors (BN-600 and BOR-60).

Design Chemical Processes for VVER-1000 SNF

Russia planned to reprocess VVER-1000 SNF at the future RT-2 plant at the Krasnoyarsk (MCC). Construction of the facility was started in the late 1980s but was never completed, although a storage pool with a capacity of 6,000 MTHM was constructed and put into operation. RT-2 was never officially canceled, and Russia still has plans to reprocess VVER-1000 SNF. If this is to be realized using new technologies, a special line for reprocessing of this SNF must be designed for RT-2 or, if the plan to complete construction of RT-2 as designed is canceled, then a reprocessing line for VVER-1000 SNF can be constructed at the operating RT-1 plant at PA "Mayak."

ASSESSMENT OF NEAR-TERM ACTIONS NEEDED IN THE UNITED STATES

In the United States, DOE and other managers of SNF and HLW have made progress in achieving interim end points: nearly all SNF in the United States is in safe storage in cooling pools or in dry casks (the notable exception is corroding SNF at Hanford); HLW at West Valley has been vitrified and HLW at the Savannah River Site is in the process of being vitrified and stored; and calcined HLW at the Idaho National Engineering and Environmental Laboratory sits in stainless steel bins that are deemed to be safe for centuries. It is the committee's judgment that there are, however, several problems that require prompt attention (over the next several years), as noted below.

Prevent Use of Nuclear Materials for Terrorist Acts

While Russia has been aware of terrorist threats, the events of September 11, 2001, forced the United States focus on preventing terrorist acts. This has led to many reviews of vulnerabilities at nuclear power stations and at all facilities where radioactive materials are stored and used. These reviews have not been completed but should be completed as quickly as feasible, and near-term actions should be taken to address the identified vulnerabilities.

Research and Develop Options for Managing HLW in Single-Shell Tanks at Hanford

Some forms of HLW in underground tanks are difficult to retrieve and, particularly in the case of single-shell tanks at Hanford, may pose substantial risks of further environmental contamination. It is not clear that existing technical solutions are adequate or acceptable for addressing this problem. Research into this problem should continue.

Accelerate Efforts to Stabilize and Package Corroding N-Reactor Fuel at Hanford

Some SNF from the N-Reactor at Hanford is in very poor condition and is stored in a cooling pool (one of the "K-basins")

which is leaking. Progress is being made, but efforts to stabilize, dry, and package this fuel should be expedited, and a disposition path should be found for the corrosion products and sludge from this fuel.

Disposition of Excess Weapons Plutonium

Disposition of excess weapons plutonium is connected to this study because the options for disposition include processing that would lead to managing the material as SNF or HLW. Russia and the United States have been working on finding disposition paths that are technically sound and that satisfy demands driven by domestic policy and international relations. From the outset, Russia has expressed its desire to fabricate plutonium-uranium mixed-oxide (MOX) fuel with the excess material, and to irradiate that fuel in existing VVER-1000 reactors and its BN-600 reactor, although Russia would prefer to use the fuel in a future BN-800. The United States has been less consistent in its planning.

Current U.S. Department of Energy plans are to complete designs for the MOX fuel-fabrication facility in 2003, to complete construction in 2004, to complete the licensing in 2005, and to begin hot startup of the facility in 2007. The first MOX fuel would be loaded into a reactor in August 2008 and full-scale operations would run from 2009 through 2019. The U.S. Congress has indicated that progress through this schedule is contingent upon progress on similar efforts in the Russian Federation, because the programs are coupled by negotiated agreement. At the same time, from a technical perspective, this is an ambitious schedule, particularly since there is not yet a decision on how to manufacture the lead test assemblies so that they can be tested (and licensed) for use in a commercial reactor, and because one of the two utilities that had originally signed up for the MOX program has pulled out. While this will not be the first MOX fuel in U.S. light-water reactors, the United States does not have any recent operational experience with MOX fuel in power reactors. Further, the composition of the Pu is different. DOE should settle on a final plan for manufacturing the lead test assemblies, and establish a schedule that will lead to putting weapons plutonium, in MOX-fuel form, in a U.S. commercial nuclear power reactor no later than 2010.

ASSESSMENT OF LONGER-TERM ACTIONS NEEDED IN THE UNITED STATES

In addition to the near-term actions listed above, the committee concluded that the following longer-term action also deserves attention in the United States.

Develop a Disposition Path for "Dirty" Plutonium

At least 2 tons of excess weapons plutonium that DOE formerly planned to immobilize have been declared to be of low enough quality ("dirty") that they cannot follow the new planned disposition path (described above) for surplus weapons-grade plutonium and no alternative disposition path has been identified. The actual quantity of this material should be clarified and a disposition path (a method for disposal) should be identified.

ASSESSMENT OF LONGER-TERM ACTIONS NEEDED IN BOTH COUNTRIES

Finally, pursuing some end points for SNF and HLW requires research, development, and implementation beyond the near term. Work is needed on aspects of every stage of the nuclear fuel cycles that Russia and the United States have as their goals: fuel fabrication, irradiation in reactors, storage in at-reactor facilities, short-term and long-term storage away from reactors, transportation, reprocessing of SNF, processing of HLW, immobilization, and disposal. Both nations also need personnel to carry out this work. The committee concluded that the following areas require attention by both the Russia and the United States.

Maintain the Expertise and Personnel Base

A critical problem for both the Russian Federation and the United States is how to assure the availability of both the current and future supply of expert scientists, engineers, and technicians needed to work on the problems related to management of SNF and HLW. Research and development concerning processing and disposal of HLW and SNF are needed to design and then implement the new strategies that will be required if we are to improve our management and disposal of these materials. Significant ad-

vances are also needed in areas related to cleanup activities in both nations.

Develop an Integrated Strategy for Management of SNF and HLW

Both the United States and Russia have numerous programs to deal with SNF and radioactive waste. Development of an integrated strategy to incorporate, as noted above, all fuel cycle elements up to the final stages should be a high priority in both countries. Without such a strategy, resources can be wasted and both safety and proliferation hazards could be left unaddressed. A strategy should include identification, stabilization, development of necessary facilities, transportation, and implementation of both interim and final end points.

Improve Chemical Processing of HLW

Progress has been made in processing HLW from defense programs for immobilization in both countries, but problems remain. These wastes have highly varied physical properties and chemical composition, so several technologies may be needed to treat all of the wastes. Development of efficient technologies for processing of different types of liquid HLW is needed. This includes the need to continue development of sludge-removal techniques for underground tanks.

Improve Waste Forms for HLW

Work is needed to develop processes for solidification and incorporation of HLW, other than that planned as feed for the Defense Waste Processing Facility, into durable glass-like and crystalline waste forms. This research would seek, select, and develop fabrication technologies for highly durable glass-like, glass-crystalline, and crystalline matrices for immobilization of different types of HLW, radioisotopes with similar characteristics, and individual radionuclides. Also needed are studies of the properties of composite materials obtained with different technologies (e.g., cold pressing and sintering, cold crucible melting, self-propagating high-temperature synthesis) to select appropriate technologies and optimize the industrial-scale fabrication process.

Improve Chemical Processing for SNF

The PUREX process, which has been used for nearly all processing of SNF in both the defense and commercial nuclear programs, generates large amounts of waste that must be further processed before being immobilized for disposal. Alternatives and improvements to the PUREX process should be carefully considered. New processes based on work done to date should be researched and considered. It may be that different fuels with different isotopic compositions should be treated separately or with different processes, particularly if the objectives are different.

General Approach to Management and Disposition

Finally, the committee draws from previous studies by the National Academies in recommending a risk-based approach to management and disposition of HLW and SNF and cleanup of contaminated sites. By a "risk-based approach," the committee means that DOE and Minatom should prioritize their efforts based first on objectively evaluated risk, which includes the specifics of the technologies, conditions, and location of their implementation. Risk analysis and characterization, and indeed the overall decision-making process, are societal processes that need participation of the public to function properly.

Once measures are taken to mitigate immediate risks, a more thorough understanding is needed for the next step, which is to assign priorities among the less immediate problems. Where effective solutions are not at hand, risks must be managed while a program of research and development (R&D) for effective solutions is pursued.

AREAS FOR COLLABORATION

Russia and the United States can collaborate on several important topics of mutual concern:

- assuring the availability of both the current and future supply of expert scientists, engineers, and technicians needed to work on SNF and HLW management;
- protecting materials useful in nuclear and radiological weapons;

- consolidating nuclear materials in a few reliably protected sites;
- counter-terrorism studies and methods;
- developing and refining technologies for safe and efficient defueling, dismantling, and disposing of decommissioned nuclear powered submarines;
- handling the legacy wastes from nuclear-weapons production;
- transporting spent nuclear fuel;
- developing standard, highly durable waste forms for immobilization of different types of HLW;
- developing methods and techniques for extraction of HLW that has been stored in tanks for decades;
- developing unified approaches to selection of geological media and sites for the HLW and SNF long-term storage and disposal; and
- research and development on methods of processing SNF that produce much less radioactive waste than the PUREX process.

In light of the terrorist attacks that have occurred in the last few years, it is worth reiterating one of the above areas for collaboration, for emphasis. Russia and the United States should prioritize working together to protect nuclear facilities from thefts of nuclear materials and from terrorist acts. The threats are present and the dangers are significant, so action should be taken without delay.

1
Introduction

Russia and the United States face many common challenges in managing spent nuclear fuel and high-level radioactive waste. Some of these challenges are rooted in the two countries' linked histories as adversaries during the Cold War, while other challenges are burdens attendant to nuclear power, which supplies a significant portion of the electricity generated in each country.[1] Russia and the United States at different times have used the same approach to addressing many of these challenges, based upon reprocessing. In recent years, however, for different reasons, they have chosen different approaches. Each approach is, in principle, technically feasible and appropriate for meeting the respective country's stated goals. Modifications to earlier approaches have been made in the United States for policy reasons and in Russia for financial reasons. Each approach has advantages and disadvantages, as well as many shared operational elements. Neither country has fully implemented its approach or realized its goals. No longer adversaries, it is in the United States' and Russia's common interests to learn more about their common problems, to learn from each other's efforts, and to ensure that high-quality science and engineering are brought to bear on these problems.

This study, requested by the U.S. Department of Energy (DOE), furthers these goals by describing the management of spent nuclear fuel (SNF) and high-level radioactive waste (HLW), and describes inventories, compares the approaches taken in the two countries, and assesses the end-point options for interim storage of materials and wastes and for permanent disposal of wastes. (See Appendix A for the statement of task.)

The report is presented in four chapters. Chapter 1 provides definitions of terms and a general overview of the problems. Chapter 2 is a technical and scientific examination of the sources,

[1]Fifteen percent in Russia (Nigmatulin 2001) and 20 percent in the United States (EIA 2002).

inventories, and planned end points for each type of SNF in Russia and the United States. Chapter 3 covers the same topics, but for HLW. In Chapter 4, the committee makes recommendations on actions that should be taken in the near term to address or prevent imminent problems, on research, development, and implementation over longer time frames, and also identifies areas for collaboration. In some cases, the recommendations simply reinforce existing plans or call for expediting planned actions, whereas in others the recommendations draw attention to apparent gaps in planning.

Constraints on the time and resources for the project limited the committee's coverage of sites and sources (specifically, the Siberian Chemical Combine at Tomsk, and the Pacific Fleet) and demanded that the committee bound its enquiry. Given the multiplicity and variation in details of interim and final end points, the committee concluded that the only feasible approach was to do an overview assessment of end points and not analyze specific options at specific sites.

Appendix A presents the statement of task for the study. Appendix B is a list of acronyms and abbreviations used in the report. Appendix C contains a brief biography of each member of the committee. Appendix D lists the meetings of the committee. Appendix E lists major laws, regulations, and other directives pertaining to radioactive waste and related issues.

1.1 DEFINITION OF TERMS

For the purposes of this committee, an end point for spent nuclear fuel or high-level radioactive waste is a stable, safe, and secure disposition of the material that can be sustained. (See Sidebar 1.1 for definitions of high-level radioactive waste and other materials discussed in this report.) The committee divides end points into two categories: interim end points, which are temporary; and final end points, which are essentially permanent. Long-term storage is an interim end point that should be sustainably stable, safe, and secure for at least several decades, and even

SIDEBAR 1.1: The definitions of HLW in the United States and Russia differ from each other.

Russia's waste classes are based on the concentration of radioactivity in the waste (Rybal'chenko et al. 1998) or on the dose rate at the surface of the waste package (NAS 1990).

High-level waste (HLW)	Any liquid waste containing greater than or equal to one curie per liter (1 Ci /liter) is HLW. Any solid waste with a dose rate greater than or equal to 1 rad per hour (1 r / hr) due to gamma radiation on the surface of the waste package is HLW.
Intermediate-level waste (ILW)	1 Ci /liter > ILW > 10^{-5} Ci /liter for liquids; 1 rad / hr > ILW > 300 mrad/hr at the package surface for solids
Medium-level waste (MLW)	300 mrad / hr > MLW > 30 mrad/hr at the package surface for solids
Low-level waste (LLW)	10^{-5} Ci /liter > LLW for liquids 30 mrad / hr > LLW at the package surface for solids

The United States' definition is based on the process that produced the waste, although it allows for other wastes to be grouped with HLW on a case-by-case basis. High-level radioactive waste is

> "(A) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and (B) other highly radioactive material that the (Nuclear Regulatory) Commission, consistent with existing law, determines by rule requires permanent isolation." [42 U.S.C. § 10101]

The U.S. Nuclear Regulatory Commission has defined spent nuclear fuel as high-level waste [10 CFR 63]. Spent nuclear fuel is fuel that has been withdrawn from a nuclear reactor following irradiation.

continues on next page

Transuranic Waste (TRUW). This class is specific to waste streams from DOE. It is

> "radioactive waste containing more than 100 nanocuries (3,700 becquerels) of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for (1) high-level radioactive waste; (2) waste that the Secretary of Energy has determined, with the concurrence of the Administrator of the Environmental Protection Agency, does not need the degree of isolation required by the 40 CFR Part 191 disposal regulations; or (3) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR Part 61" (DOE 2001a).

Low-Level Waste (LLW)

> "[R]adioactive material that - (A) is not high-level radioactive waste, spent nuclear fuel, or byproduct material (as defined in 42 U.S.C. § 2014); and (B) the Nuclear Regulatory Commission, consistent with existing law and in accordance with paragraph (A), classifies as low-level radioactive waste" (42 U.S.C. § 2021).

In the government sector, TRUW is also excluded from LLW.

LLW is divided into two broad categories: waste that qualifies for near-surface burial and waste that requires deeper disposal ("Greater than Class C LLW," or "greater confinement waste") (10 C.F.R. 61). Among wastes that qualify for near-surface disposal, Class C LLW has the highest concentrations of long-lived radionuclides.

While these definitions are different, most of the material that would be considered HLW in one country would also be considered HLW, or treated like HLW, in the other country. This report covers any SNF or HLW that fits the definition of either country.

longer, so long as the necessary resources are supplied.[2] Geologic disposal is a final end point that should be sustainably sta-

[2]The U.S. Nuclear Regulatory Commission, in 1990, issued a finding called the Waste Confidence Decision, which concerns storage of spent nuclear fuel and the future availability of a high-level waste repository in the United States. The decision is, in part, a "generic determination that, if necessary, spent fuel generated in any reactor can be stored safely and without significant environmental impacts for at least 30 years beyond the licensed life for operation of that reactor

ble, safe, and secure beyond the duration of the hazards posed by the waste or for at least thousands of years. While disposition that is stable, safe, and secure for shorter periods, such as a few years, logically fits the definition provided above, it is not considered an end point for the purposes of this study.

Other steps in the nuclear fuel cycle, such as conversion of separated plutonium for fabrication into MOX fuel or irradiation ("burning") of spent fuel in a reactor, might be steps toward an end point but they are not end points. This is because each of these steps produces radioactive waste that requires storage and, eventually, disposal.

1.1.1 Safety

Safety must be a major consideration whenever working with radioactive materials. Special care must be taken when this involves materials capable of a nuclear explosion. To prevent the latter, criticality analyses must be done to provide guidelines to prevent criticality events. When such guidelines are not followed, accidents such as that at the Tokaimura plant in 1999 (IAEA 1999a) can occur, causing loss of life and severe radiation exposure. HLW, by its very nature, poses extreme radiation hazards and must be handled and stored with great attention to prevent worker exposure and accidents that could lead to both worker and public exposure. Safe end points, from a radiological perspective, are those end points that prevent harmful releases of radionuclides to the environment and direct exposures of people (workers and the public). These goals are generally well known, and are treated only in the simplest of terms here. Preventing releases and exposures mostly means containing radionuclides, shielding radiation sources, cooling highly radioactive materials, and preventing criticality events. Large inventories of radionuclides have entered the environment as results of leaks, accidents, and intentional releases (see Sections 3.1 and 3.2 of this report). Once in the environment, radionuclides can enter food chains and water supplies and cause detrimental health effects. Many radioactive wastes contain chemically hazardous materials (toxic, caustic,

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at its spent fuel storage basin or at either onsite or offsite independent spent fuel storage installations" (U.S. NRC 2003).

flammable etc.), so the wastes, and any contamination from them, can impose hazards that are not just radiological in character.

1.1.2 Security

Radioactive materials—like many other toxic substances—can be used intentionally either to help (medical applications, non-destructive testing) or to harm people. Preventing proliferation of nuclear materials has been a security concern for a half-century, and in the last few years there have been concerns in Russia and in many other countries possessing such materials about terrorist use of radiation sources. There now is, however, heightened awareness of a multitude of security concerns, including those related to SNF and HLW, since the terrorist bombings of residential apartment buildings in Russia in September of 1999 and August of 2000, the terrorist attacks in the United States on September 11, 2001, and most recently the attack on a Moscow theater in October of 2002. A thorough treatment of the topics of nuclear proliferation and terrorism is well beyond the scope of this study, and many of the details on these topics are considered classified information. But nuclear proliferation and terrorism are important considerations in assessment of interim and final end points for SNF and HLW. Several recent and ongoing studies examine these threats. The following overview of the threats and of measures that can be taken to reduce the risks of nuclear proliferation and terrorism is drawn from the National Research Council report *Making the Nation Safer* (NRC 2002a).

There are two main types of weapons that use radioactive material: radiological weapons and nuclear weapons.

Radiological weapons cause radiation exposures by dispersing radioactive material or by locating a large radiation source where it will expose people directly. Dispersal can be achieved by attacking a nuclear facility, such as a nuclear reactor, a SNF-storage facility, a HLW tank, or radioactive waste in transit, or by constructing a radiological dispersion device, sometimes called a "dirty bomb," in which the radioactive material is incorporated into the device prior to the attack.[3] Casks for storage and transport of SNF are generally very robust and it would be extremely difficult

[3]HLW and SNF are not the only radioactive materials that can be used for radiological weapons. Radiation sources used in the manufacturing industry, medical treatment, and food irradiation could be used by terrorists, but these materials are outside of the scope of this study.

to breach them and cause substantial dispersal of the contents. Although freshly discharged SNF is highly radioactive and cooling is needed to prevent the SNF from reaching temperatures that breach the fuel cladding, SNF stored in cooling pools at U.S. power plants is not generally seen as vulnerable. It should be noted, however, that each plant is different and analyses are on going (NRC 2002a). Most storage tanks for HLW are underground and are located on guarded facilities in relatively remote areas. Exposures from radiological weapons are unlikely to cause large numbers of fatalities, and are unlikely to cause any fatalities unless the material dispersed is highly radioactive. Dispersal of even small amounts of radioactivity in populated civilian areas, however, could cause panic and major disruption, and could be very expensive to clean up.

Nuclear weapons use fission and sometimes fusion reactions to achieve large explosive yields and, in so doing, release a large burst of radiation and disperse the radioactive products of fission and neutron-activation reactions. Achieving a nuclear yield requires fissile material,[4] knowledge of how to design a weapon, and some additional equipment. Access to fissile material is regarded as the greatest barrier to building a nuclear weapon. Fissile material is found in low concentrations in power-reactor SNF, and in higher concentrations in SNF from other reactors, such as propulsion reactors and research reactors, which commonly have highly enriched uranium (HEU) fuel.[5] The other major source of fissile material that is attractive for those trying to build weapons is material for and from nuclear weapons stockpiles. According to data from American reports (NAS 1994, Albright and O'Neill 1999; DOE 2000a; NRC 2002a; Bunn et al. 2002), the United States and the Soviet Union each accumulated on the order of 1,000 tons of HEU (together, enough for over 150,000 bombs). These same reports indicate that the Soviet Union produced approximately 150 tons of weapons-grade plutonium, and the United States produced approximately 100 tons (enough for at least another 60,000

[4]Fissile materials are those that fission when exposed to low-energy neutrons. Most important among the fissile isotopes are uranium-235, plutonium-239, and uranium-233, in that order. Nuclear yields are technically achievable with non-fissile fissionable isotopes, such as plutonium-240, but the practical difficulties of making a weapon from these isotopes makes them a lesser concern.

[5]Highly enriched uranium is uranium containing at least 20 percent uranium-235 by mass.

bombs, combined).[6] Efforts to reduce the stockpile of excess weapons plutonium are described in Section 2.2.3 of this report. Of special concern, however, is HEU, because while one needs a larger mass of HEU to make a nuclear weapon, HEU is harder to detect, and design of an HEU weapon is simpler. Nuclear weapons, even low-yield nuclear weapons, are capable of large-scale devastation and could in one blast result in casualties that exceed those resulting from protracted military conflicts.

Nuclear weapons, then, are the gravest concern and preventing theft of fissile materials is among the highest priorities. To that end, sites that have fissile material need to have a strong materials protection, control, and accounting (MPC&A) program for those materials. It is easier to carry out such programs at a small number of sites than at a large number of sites, so consolidation of fissile materials to protected sites with effective MPC&A programs reduces risks. Reducing the inventories of these materials or making them less attractive with a radiation barrier or isotopic dilution also reduces risks. For example, mixing plutonium with HLW or irradiating it in a reactor provides a strong field of radiation around the plutonium, and irradiation reduces the percentage of plutonium-239, the most attractive plutonium isotope for making nuclear weapons.

While the consequences of radiological attacks are less dire, such attacks are easier to carry out, due to easier access to radiation sources. Similar measures to those recommended for fissile materials—consolidation of strong radiation sources, reductions in inventories, conversion to unattractive forms—also reduce risks of radiological attacks.

1.2 BACKGROUND AND OVERVIEW OF THE CHALLENGES

During the last three years of World War II the United States initiated, pursued, and succeeded in an effort to develop nuclear bombs. The first nuclear bomb was detonated on July 16,

[6]According to NRC (2002a), there are estimated to be about 1,200 metric tons of HEU and about 150 metric tons of separated plutonium in addition to the inventory in weapons in Russia. The amount of plutonium per weapon is taken to be 4 kg, after NAS (1994). The U.S. inventory of separated plutonium is 99.5 metric tons according to DOE (2000a) and the U.S. inventory of HEU is 635 metric tons (plus or minus 10 percent) according to Albright and O'Neill (1999). The amount of HEU per bomb is taken to be 12 kilograms, after Bunn et al. (2002).

1945. The plutonium used to construct that bomb was produced at the Hanford facility, in Washington State, in the northwestern United States. The land for the Hanford facility was purchased only in 1943 and within two years fuel-fabrication facilities, reactors, processing facilities, and underground storage tanks had been built and put in operation (Gephart and Lundgren 1998).

Immediately following World War II, the Soviet Union embarked on its own program to build nuclear weapons. In 1946, construction began at a site selected for a plutonium-production facility called "Mayak,"[7] located on the eastern slope of the Ural mountain range, approximately 120 km south of the city of Sverdlovsk (now renamed Yekaterinburg) by a town now called Ozersk. The facility's first plutonium-production reactor began full-power operations in June 1948 and the reprocessing plant received irradiated metal for separations in December of that year. Finished, separated plutonium was produced in February 1949, and on August 29, 1949, the Soviet Union detonated a nuclear bomb similar in design to the U.S. bomb dropped on Nagasaki.

The people who worked for the nuclear weapons programs in each nation accomplished feats of scientific and engineering design, as well as construction and operation, that would be remarkable if they took place over a period of two decades. However, the rush to produce nuclear weapons led to profound and, in some cases, widespread environmental contamination. In the context of World War II and the Cold War that followed, the pressures and priorities were on production of weapons material, not on minimization of wastes, environmental impacts, or even—at least in the earliest years—worker and public exposures. Further, production was implemented and increased faster than understanding of the environmental impacts developed. Addressing all but the immediate problems associated with radioactive waste was postponed. As a result, some foreseeable problems arose but were not dealt with, and other problems arose as surprises.

In the decade following the first development and use of nuclear weapons, nuclear reactors were also developed for other purposes: generation of electricity, propulsion of warships and other maritime vessels, and research and testing. In 1951, a nuclear reactor at a laboratory in Idaho in the United States produced approximately 400 watts of electricity. In 1954, at a labora-

[7]The name "Mayak" means "beacon," indicating those who show the way.

tory in Obninsk, the Soviet Union operated the world's first nuclear power plant for generating electricity. The 5 MWe (30 MWth)[8] graphite-moderated, water-cooled power plant (AM-1) generated electricity until 1959 and was operated for research and isotope production until 2002 (Bellona 2002; IAEA 1999b). The Soviet Union's nuclear power industry started a handful of power reactors in the 1960s, roughly tripled the number during the 1970s, and brought dozens of reactors into service during the 1980s. Russia now has 30 operating power reactors at 10 different sites within its borders.[9] All but one of Russia's nuclear power plants are run by the Russian State Concern for Generation of Electric and Thermal Power at Nuclear Power Plants ("Rosenergoatom").[10]

The amounts of SNF currently stored in the Russian Federation and the United States are presented in Table 1.1, along with the rate at which the inventory is increasing. These data are presented by the type of reactor fuel, and are taken from various sources that are referenced elsewhere in this report. In 2001, the amount of SNF from Russian nuclear power plants was estimated to be about 14,000 MTHM[11] (with radioactivity of over 5 billion curies), and to be growing at a rate of approximately 850 MTHM per year. The Soviet Union also constructed 38 power reactors in Eastern Europe, Ukraine, Finland, and Lithuania. The Russian Federation has stated its intention to fulfill the original Soviet program to take back the SNF from those reactors, and is currently storing and reprocessing SNF from at least some of them for a fee.

Civilian nuclear power (generally referred to as commercial nuclear power) in the United States began in 1957 and several more plants were added during the 1960s, but dramatic growth took place in the 1970s. The United States now has 103 pressurized-water and boiling-water nuclear power reactors operating at 65 different sites. This is the largest number of power reactors, and the largest nuclear generating capacity, of any nation. No new

[8]MWe means megawatts electric and MWth means megawatts thermal.

[9]Nuclear News (2002) reports 30 plants at 10 sites as of December 31, 2001, including the Rostov plant, which went into operation in December 2001.

[10]Leningrad Nuclear Power Plant, comprising 4 RBMK-type units rated at a combined total power of 4,000 MWe, is an independent operating utility and reports directly to the Ministry of Atomic Energy of the Russian Federation (Minatom).

[11]MTHM stands for "metric tons of heavy metal," where "heavy metal" refers to the actinide content of the fuel before irradiation in a reactor. This does not include the mass of other constituents of the fuel.

TABLE 1.1 Amounts of Spent Nuclear Fuel in Storage and Rate at Which the Amount is Increasing

Type of Spent Nuclear Fuel	Russian Federation Spent Nuclear Fuel (MTHM)	United States of America Spent Nuclear Fuel (MTHM)
Power Reactor	14,000 + 850 per year	45,000 + 2000 per year
Naval	70 + fuel from 15-18 NPSs per year	19.5 + 45.5 over 33 years[a]
Production Reactor	Not available [b]	2100 + 0 per year
Research Reactors	28,500 assemblies	23 + 0.7 per year

[a]Citing an annual rate for discharges from naval reactors may not be accurate, so the expected total for a known period is given.

[b]Approximately 1.5 MT of separated Pu are produced each year by the three dual-purpose reactors (see Section 2.1.2). The SNF from these reactors is stored only briefly before going through chemical separations.

nuclear power plants have been ordered in the United States for over two decades, but recently there has been talk of expanding the nuclear power industry and building new plants. Nuclear power reactors generated most of the SNF in the United States (approximately 45,000 MTHM as of December 31, 2001 [Holt 2002]), and the SNF is stored at commercial facilities where the reactors are located.

Most of the power reactors are not owned by the government,[12] but the federal government has a legal obligation to take ownership of the SNF and ultimately to dispose of it.

In the same year that the Soviet AM-1 reactor came online, the United States launched the first nuclear-powered submarine, the Nautilus. The U.S. Navy has launched a total of 210 nuclear ships, 128 of which have been removed from service.

The Soviet Navy launched some 248 nuclear-powered ships, including 244 submarines (Moltz 2000), most powered by two reactors (Nilsen et al. 1996). As of January 2002, 190 Russian submarines had been retired from service. Maritime reactors have generated a larger amount of SNF in Russia than they have in the United States because the U.S.S.R.'s nuclear navy was somewhat larger than that of the United States and used more fuel in each reactor (more reactors in each ship, refueled more frequently).

[12]Nuclear reactors in the Tennessee Valley Authority (TVA) and Bonneville Power systems are federally owned. In addition, a few reactors are partially or totally owned by state governments.

In 1957, the Soviet Union launched the world's first nuclear-powered surface ship, the icebreaker Lenin, which was decommissioned in 1989. The Murmansk Shipping Company now operates Russia's 8 state-owned, nuclear-powered civilian vessels (seven icebreakers and one nuclear-powered container ship). The United States has no civilian nuclear ships, although it did have one cargo ship during the 1960s.

All fission reactors irradiate nuclear fuel and generate fission products and activation products within the fuel. These radioisotopes, along with the fissile material initially contained in the fuel, are the sources of concern for accidents, handling and disposal, and proliferation.

All reactors used for production of plutonium in the United States have been shut down. As of 2002, the federal government had accumulated various kinds of SNF totalling 2,411 MTHM that are ultimately destined for direct disposal (DOE 2002a), a number that is expected to grow to only 2,477 MTHM by 2035.

In both Russia and the United States, the majority (by volume) of HLW was generated as part of the weapons programs, although in Russia that is likely to change as more fuel from power reactors is reprocessed. In Russia, HLW has accumulated primarily at the Production Association "Mayak" (PA "Mayak"), the Mining and Chemical Combine (MCC) at Krasnoyarsk-26, and the Siberian Chemical Combine (SCC) at Tomsk-7. Low- and intermediate-level liquid waste has been injected into hydraulically isolated permeable horizons at the Krasnoyarsk MCC, SCC, and the Scientific Research Institute of Nuclear Reactors (NIIAR, near Dmitrovgrad) sites (see Rybal'chenko et al. 1994, 1998).

In the initial stages of operation of PA "Mayak" (before 1951), liquid radioactive wastes were dumped into the Techa River. Later, intermediate-level liquid radioactive wastes were dumped into Karachai Lake, and low-level wastes were piped into the Techa Ponds Cascade. Liquid HLW accumulated from defense program and SNF reprocessing are stored in the special tanks at PA "Mayak," SCC, and MCC.

In the United States, HLW has accumulated at the Hanford Reservation and the Savannah River Site (SRS), which have the greatest volumes of HLW, and at the Idaho National Engineering and Environmental Laboratory (INEEL), and a much smaller amount of vitrified HLW is at the West Valley Demonstration Project. In total, in 1997 the United States had approximately 380,000 cubic meters of HLW (DOE 1997a). The tanks at Hanford and at

SRS were not designed for indefinite storage and 67 at Hanford and 1 at SRS have leaked into the environment. At INEEL, which converted its HLW into a "calcine powder" and stored it in stainless steel silos, some HLW leaked into the subsurface during operations due to faulty valves and a transfer line that was severed.

1.3 NUCLEAR FUEL CYCLES

Although the plutonium-production process was quite similar in both the United States and the Soviet Union, the two countries (and later Russia) chose to pursue different long-term goals in what is called the nuclear fuel cycle—that is, the flow of fissile and other nuclear materials in production of nuclear energy. The most radioactive constituents of the plutonium-production process and the nuclear fuel cycle are spent nuclear fuel (SNF) and high-level radioactive waste (HLW). SNF is nuclear fuel that has been irradiated in a reactor. In the plutonium-production process and in a "closed" nuclear fuel cycle[13] (see Figure 1.1), SNF is an interim state for the nuclear material, after irradiation and before chemical processing. The chemical processing typically separates at least the uranium and plutonium in the SNF from the fission products and higher actinides (such as americium and curium). In an "open" or "once-through" nuclear fuel cycle (see Figure 1.2), the material in SNF is not considered for further use in a reactor. After it is discharged from a reactor, the SNF is stored, allowing it to cool, and then it is to be sent to a geologic repository for disposal.

The Soviet Union reprocessed irradiated fuel and targets for its weapons program at its radiochemical plants at PA "Mayak," the SCC at Tomsk-7, and the MCC at Krasnoyarsk-26 during the 1960s and early 1970s. The SCC and Krasnoyarsk MCC are still reprocessing, and storing the products. In 1976, a reconstructed radiochemical plant at PA "Mayak" called RT-1, with new process lines, began to accept and reprocess spent fuel from VVER-440, BN-600, research, and naval propulsion reactors. The processing capacity of RT-1 was increased in stages and now is 400 MTHM per year, although it now operates at about half its capacity.

[13] "Closed nuclear fuel cycle" is a misnomer, since this fuel cycle still produces radioactive waste, which requires safe disposition.

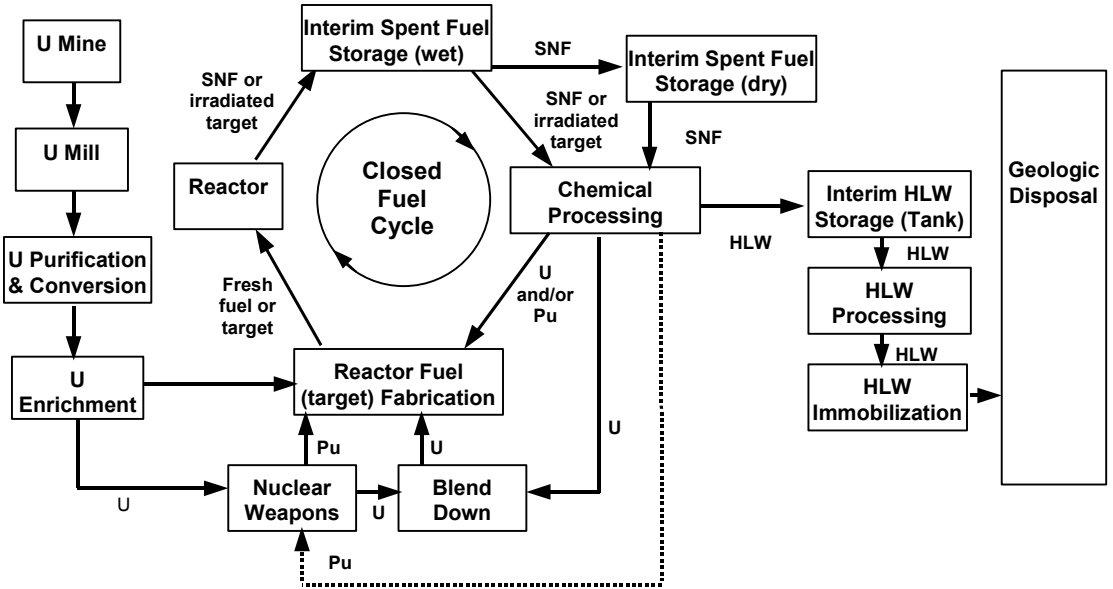

FIGURE 1.1 Material-flow diagram of a closed nuclear fuel cycle. A plutonium-production process diagram has nearly identical components except that the reactor irradiates uranium targets, which are processed to recover Pu (see the dotted line from chemical processing to nuclear weapons).

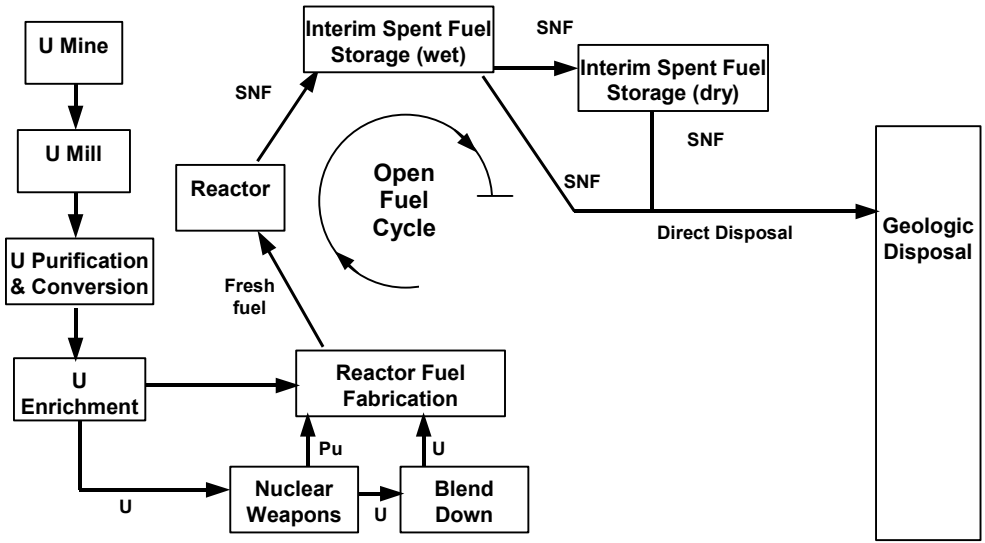

FIGURE 1.2 Material-flow diagram of an open nuclear fuel cycle.

Fuel from VVER-1000 reactors also was supposed to be sent for reprocessing, but it could not be processed using any of the RT-1 lines, so construction began on another reprocessing plant, RT-2, at the Krasnoyarsk MCC in 1984. Construction stopped in 1989 due to lack of funds. Spent fuel from VVER-1000 reactors is currently shipped to the Krasnoyarsk MCC, where it is stored in a large cooling pool. Current plans (Minatom 2000) call for use of some of RT-2's partially completed buildings to store spent fuel and for construction of RT-2 to be completed in the period 2020-2025 and begin operation in the period 2025-2030.

In the United States, essentially all SNF was reprocessed initially or stored with the intent to reprocess it later to recover uranium and plutonium. This was true of production fuel at the plutonium production facilities, fuel from the nuclear-powered naval ships, and SNF from experimental reactors. Most of the reprocessing capacity at the U.S. nuclear weapons sites has been shut down. The remaining facilities are the two "canyons" (F and H) at SRS and experimental scale equipment at the Argonne National Laboratory West, which are to be used to process spent nuclear fuel that is either unstable or unsuitable for disposal in its current form.

As civilian nuclear power plants began to operate and nuclear energy began to grow, new facilities were required to carry out reprocessing of SNF. The federal government in the United States encouraged development of reprocessing by private industry to serve the commercial nuclear power industry. Two commercial reprocessing facilities were built in the United States, although one never operated. In 1977, before construction on the third plant was completed, U.S. President Carter formalized a policy begun under President Ford to defer indefinitely "the commercial reprocessing and recycling of plutonium in the U.S." (Carter 1977a). President Carter indicated that no federal government funding would be provided for reprocessing of commercial SNF.[14] Although President Reagan endorsed commercial reproc-

[14]The President does not have authority to prevent licensing of a reprocessing facility proposed by a private entity under the Atomic Energy Act, but the company seeking to build a reprocessing plant in Barnwell, South Carolina, Allied General Nuclear Services, needed federal government funds to complete the plant. "The U.S. will indefinitely defer the commercial reprocessing and recycling of the plutonium produced in the U.S. nuclear power programs...The plant at Barnwell, South Carolina, will receive neither Federal encouragement nor funding for its completion as a reprocessing facility" (Carter 1977b). President Carter also asked the U.S. NRC to suspend licensing proceedings until two studies on nuclear fuel cycles could be completed. Allied General did not request that the licensing proceedings be reopened after the studies were published in 1980. At

essing in 1981, he did not offer federal government funding and no one has pursued a license to reprocess commercial SNF in the United States since the policy began. Instead, SNF is being stored until a repository is available for permanent disposal of the SNF as waste, an approach that is called the "once-through" fuel cycle, referring to the number of times the material fuels a reactor core, or as "direct disposal." Under current conditions in the United States, reprocessing is deemed uneconomic and, by some, politically undesirable. However, the current Administration has asked for this to be reconsidered. [15]

As mentioned earlier, Russia and the United States currently have some differences in philosophy on the desired fuel cycle, but in practice there are many similarities. In both nations, the majority of SNF will be stored for at least two decades. The United States has planned for more than 20 years to complete the "back end" of the fuel cycle by sending the SNF and HLW to an underground repository.

This year 2002 is an important year with respect to political progress toward a repository in the United States. The President of the United States and the U.S. Congress decided that the federal government should pursue a license to construct a geologic repository at the only U.S. candidate site, Yucca Mountain. But even with approval from Congress, SNF would not go underground at that site until at least 2010. The repository program must seek a license to construct the repository, it must build the repository, it must seek a license to operate the repository, and it must then ship the SNF to the repository for disposal. DOE projects that shipments of SNF will be spread out over 24 years. In the meantime, SNF is to be stored and HLW is to be immobilized and stored. (However, the current Administration is examining other paths in the new Nuclear Fuel Cycle Initiative, linked to the National Energy Policy statement in Footnote 15.)

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issue was whether issuing a license "would be inimical to the common defense and security or to the health and safety of the public" (42 U.S.C. 2133(d), 2134(d)).

[15]"The United States should also consider technologies (in collaboration with international partners with highly developed fuel cycles and a record of collaboration) to develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation resistant" (National Energy Policy Development Group 2001).

Constructing and operating new facilities for reprocessing Russia's spent fuel and using the separated uranium, plutonium, and even the minor actinides in fuel for fast reactors would realize the goal of a closed fuel cycle. With today's facilities, SNF from only some of Russia's power reactors can be reprocessed and only the uranium is recycled. Russia currently separates the low-enrichment uranium from its VVER-400 reactors and mixes that uranium with more highly enriched uranium from its naval reactor SNF, BN-600 SNF, and research reactor SNF. The resulting uranium is used in fresh fuel for RBMK reactors. Plutonium also is separated and stored, and is planned to be used in the future in mixed oxide (MOX) fuel, and some test assemblies of MOX fuel have been tested successfully in the BOR-60 and BN-600 reactors.

The United States and Russia plan to make MOX fuel from plutonium declared "excess to national defense needs," mostly through reductions in their stockpiles of nuclear weapons. There are no current plans to reprocess RBMK fuel, although earlier plans were to reprocess RBMK fuel at the RT-2 facility. Russia has taken only preliminary steps toward creating HLW repositories, which are required even as part of a "closed" nuclear fuel cycle.

2
Spent Nuclear Fuel and End Points

This chapter describes sources, inventories, and end points for spent nuclear fuel in Russia and the United States.

2.1 SPENT NUCLEAR FUEL IN THE RUSSIAN FEDERATION

According to the Russian Federation law "On the Use of Atomic Energy," irradiated nuclear fuel is considered a valuable raw material for recovery of nuclear fuel components and certain isotopes. At the same time, irradiated nuclear fuel is a potentially hazardous product as well as a potential source of plutonium, which is a proliferation risk.

At the end of 2001 there were 13,515 metric tons of heavy metal (MTHM) of irradiated nuclear fuel at the Russian nuclear power plant and radiochemical plant storage facilities (Shatalov 2002) (see Tables 2.1 and 2.2). The annual growth of the SNF inventory in Russia is about 850 MTHM, nearly all from nuclear power operations in Russia, Ukraine, and Bulgaria. The total radioactivity of spent nuclear fuel accumulated in Russia comprises about 4.65×10^9 curies (Ci).

2.1.1 Power-Reactor Spent Fuel in the Russian Federation

Of the four types of power reactors that operate in Russia, two types generate most of the power: boiling water graphite reactors (the RBMK reactors), and pressurized water reactors (the VVER reactors). RBMK-1000 reactors use UO_2 fuel pellets containing 2.0-2.4 percent U-235 (the fissile isotope of natural uranium). The pellets are sealed in zirconium alloy rods, which are bundled into assemblies of 18 rods. Each assembly is inserted into a pressure tube or coolant channel. Water flow through a

coolant channel can be stopped during reactor operation, allowing for online refueling. RBMK fuel enriched to 2 percent typically reaches an average burnup of about 30,000 megawatt days per metric ton of heavy metal (MWd/MTHM).[1]

The VVER reactors operate with UO_2 fuel enriched to 3.0-4.4 percent,[2] sealed in zirconium alloy rods. The VVER rods are roughly half the length of RBMK assemblies. The rods are removed during refueling outages, one to two years apart (depending on fuel enrichment). VVER fuel typically reaches an average burnup of approximately 50,000 MWd/MTHM in a VVER-440 and 40,000-45,000 MWd/MTHM in a VVER-1000. The other two types of reactors are the liquid metal fast reactors (BN series), only one of which, the BN-600, now operates as a commercial power reactor, (the BOR-60 operates as a pilot power station), and the Bilibino boiling water graphite reactors (EGP-6 reactors), which are small versions of the RBMK reactors. The BN-600 at the Beloyarsk nuclear power station is cooled with sodium and has steel-clad UO_2 fuel, enriched to 17-33 percent.

Six VVER-440 reactors (pressurized water reactors) operate in Russia and generate 87 MTHM of SNF annually. After discharge from the reactors, the SNF is stored in cooling pools for a period of 3-5 years, and then it is shipped in casks to the reprocessing plant, RT-1, at PA “Mayak.” The cooling pools at the reactor sites are typically filled only to 20-25 percent of their capacity. If shipments of the SNF offsite were to halt, however, the pools would be filled in four to five years. Breached SNF assemblies (now numbering 60) from VVER-440 reactors are stored in separate sections of the cooling pools. These assemblies are expected to be shipped to the RT-1 plant for reprocessing by 2007.

Another 21 VVER-440 reactors operate in European countries outside of Russia. Shipments of VVER-440 SNF from these countries to Russia have diminished in recent years. As noted earlier, Russia intends to take back the SNF from those reactors, and is currently storing and reprocessing SNF from at least some of them for a fee. Seven VVER-1000 reactors operate in Russia and generate 190 MTHM of SNF annually. Another 17 VVER-1000

[1]The theoretical maximum burnup for fuel of this composition—that is, the energy released if every nucleus of uranium were fissioned—is approximately 940,000 MWd/MTHM.

[2]Enrichment is 3.6 percent on average for VVER-440s and either 3.3 or 4.4 percent for VVER-1000, depending upon the length of the operating cycle (Rosenergoatom 2002).

TABLE 2.1 Data on SNF Inventory in Russia

Nuclear Power Plants and Other Nuclear Facilities	SNF Inventory at the End of 2001, MTHM	Reactor Type	Number of Operating Reactors
Leningrad	3,720	RBMK-1000	4
Smolensk	1,830	RBMK-1000	3
Kursk	3,230	RBMK-1000	4
Total RBMK	**8,780**		**11**
Balakovsk	344	VVER-1000	4
Kalininsk	172	VVER-1000	2
Novovoronezh	163	VVER-1000	1
Rostov[a]		VVER-1000	1
Total VVER-1000	**679**		**8**
Novovoronezh	71	VVER-440	2
Kolsk	112	VVER-440	4
Total VVER-440	**183**		**6**
Bilibinsk	123	EGP-6	4
Beloyarsk	59	BN-600	1
	190	AMB	
Total Nuclear Power Plants	**10,020**		**30**
PA “Mayak”	486	NA	
Krasnoyarsk MCC	2,840	NA	
NIIAR	122	NA	
Kurchatov Research Center	3	NA	
IPPE	14	NA	
NIKIET	1	NA	
Tomsk SCC	32	NA	
Total for Russian Federation	**13,520**		

[a]Rostov is a new power plant and no SNF had been discharged as of the end of 2001.
SOURCE: Shatalov (2002).

TABLE 2.2 Aggregated Data for the End of 2001 on Amounts of Spent Nuclear Fuel and Radioactive Waste at Nuclear-Powered Submarines (NPSs) Destined for Dismantling, Floating Technical Bases, Shore Bases, and Plants Carrying Out Dismantling Work

Object name	Units	NPS Compartments		Quantity of Solid RW		Quantity of Liquid RW		Total Activity
	Number	Number	Ci	m^3	Ci	m^3	Ci	Ci
NPSs with unloaded SNF	29			18,000	3.0×10^6	1,200	12	3.0×10^6
NPSs awaiting unloading of SNF	93	170	1.8×10^8	54,000	1.7×10^7	3,600	36	2.0×10^8
Floating technical bases	41	20	2.0×10^7			3,600	30	2.0×10^7
Shore bases of northern Region	2	116	5.0×10^7	4,600	6.0×10^3	3,200	60	5.0×10^7
Shore bases of Pacific Region	2	40	2.0×10^7	15,500	1.6×10^5	2,100	40	2.0×10^7
Plants that dismantle NPSs	8			2,000	3.0×10^2	2,500	30	3.3×10^2

SOURCE: Shatalov (2002).

reactors operate outside of Russia, and several others are in the design and construction stage. Spent fuel from VVER-1000 reactors is not currently reprocessed: After 3-5 years of storage in cooling pools at the power plants, the assemblies are shipped to a centralized storage facility at the Krasnoyarsk MCC.

Eleven RBMK-1000 reactors operating in Russia generate 550 MTHM of SNF (about 5,000 fuel assemblies) annually. Two AMB reactors (earlier versions of the RBMK reactor), located at the Beloyarsk nuclear power plant, were decommissioned in 1983 and 1990 (IAEA 2001).

Four EGP-6 reactors (graphite-moderated boiling-water reactors for combined heat and power, each generating 62 MWth) located at one power station in Bilibino are planned to be finally decommissioned in 2004.

Unit 3 of the Beloyarsk nuclear power station is a BN-600 reactor. The BN-600 has operated since 1980, producing roughly 3.8 MTHM of SNF per year (CEG 2000), and is licensed to operate through 2010. The SNF from this reactor is reprocessed at RT-1.

2.1.2 Government-Managed Spent Nuclear Fuel in the Russian Federation

Management of SNF from weapons production, naval vessels, and research reactors is paid for by the federal government.

Weapons-Production Spent Nuclear Fuel

Three dual-purpose reactors (production of plutonium and power) still operate in the Russian Federation: one at the Krasnoyarsk MCC and two (ADE-4 and ADE-5) at the SCC. These reactors continue to operate because the nearby cities need the heat and electricity that the reactors produce. The fuel from these reactors does not accumulate because it is reprocessed at onsite facilities. Roughly 1.5 MTHM of plutonium are generated by these reactors (500 kg each) annually and placed in storage as an oxide (Diakov 1995). Reprocessing of this SNF generates liquid and solid radioactive wastes.

Maritime Spent Nuclear Fuel

As noted earlier, the Soviet Navy launched some 248 nuclear-powered ships, including 244 submarines, most powered by two reactors.[3] The other vessels were cruisers and research and support vessels. As of July 2002, 190 Russian submarines have been retired from service. The majority of these, 114, are from the Northern Fleet and sit in various conditions at the bases along the shore of the Kola Peninsula. The remainder, 76, are from the Pacific Fleet at bases along the coast of Vladivostok (54 in Primorsky region) and on the Kamchatka Peninsula (22 in Kamchatka).

By early 2001, about 70 tons of SNF (including breached assemblies) had accumulated from the transport nuclear installations at the Russian Navy's shore bases and floating technical bases (a refueling and service ship). The total radioactivity of that accumulated SNF is estimated to be 200 million curies. The status of many assemblies is unknown. As part of decommissioning of nuclear submarines, the unloaded reactor compartments (along with adjacent compartments that add buoyancy) are cut from the rest of the vessel, and are left floating, moored in place, for storage. Beginning in 2002, the rate at which SNF is unloaded from operating and decommissioned transport installations is expected to be in the range 15-18 NPSs per year.

The SNF from nuclear-powered ships in Russia is generally described as reprocessible or unreprocessible. The latter category includes defect fuel, damaged fuel,[4] fuel encased in solidified metal coolant, and fuel for which existing reprocessing facilities do not have appropriate process lines due to the fuel's composition (e.g., U-Zr and U-Be fuel). Reprocessing of defect fuel requires new technological solutions (control systems, packaging in tight containers, development of the method for reprocessing in containers). Reprocessing of defect fuel is to be taken into account when the RT-1 undergoes plant reconstruction (planned for 2005-2007). According to the Russian strategy for SNF management (CEG 2000), damaged cores will stay at the na-

[3]Forty-six Soviet submarines, including mini-submarines, were built with only one reactor each. Seven of these were built with liquid-metal-cooled reactors (LMRs), rather than the standard pressurized-water reactors (PWRs), using lead-bismuth eutectic (a prototype LMR submarine had two reactors) (Nilsen et al. 1996).

[4]Defect fuel includes assemblies with structural damage (swelling, bending, leakage, etc.). Damaged fuel is fuel that was damaged as a result of an accident and now is not retrievable from the cores.

val bases until the cores can be safely disposed.[5] Reprocessible fuels are planned to be transported to PA "Mayak" for radiochemical reprocessing. The defect fuel is also planned to be reprocessed after storage. Plans are not yet in place for unreprocessible fuel.

Northern Fleet[6]

As noted previously, 114 nuclear-powered submarines (NPS) had been decommissioned from the Russian Navy in northwestern Russia, as of July 2002. Seventeen NPSs will be defuelled in 2002. Defueling of NPSs currently designated for decommissioning is anticipated to be completed by 2007.

Two stand-prototypes (on-land test reactors) of the ship-based nuclear power plants are in operation in Russia, in Obninsk. The SNF from these stand-prototypes, totaling several tons, is stored in cooling ponds at the sites. Three stand-prototypes of space nuclear power installations were also constructed and operated in Russia. The SNF from these reactors (about 500 kg) is stored in dry storage facilities at the sites.

Research and Test Reactor Spent Nuclear Fuel

According to the IAEA research reactor data base (1999b), there are 51 research reactors in the Russian Federation: 28 operating, 12 decommissioned, and 11 shut down. At least one of the reactors reported as operating has since shut down (Bellona 2002). In addition, there are 46 critical assemblies: 29 operating and 17 shut down. Kozlov et al. (2002) report an inventory of roughly 28,500 spent fuel assemblies at 24 of the research reactors. Fourteen research reactors outside of Russia expect to send their SNF to Russia for disposition.

Because of the diversity in the construction of the fuel rods and fuel assemblies and differences in fuel composition and structural materials, a decision will be made for each research re-

[5]An alternative for management of damaged cores is placing cut-off reactor compartments in inactive, large-diameter strategic missile compartments. The method proposed would, it is hoped, safely isolate damaged reactor compartments from the biosphere for at least 25 years. (Ruzankin and Makeyenko 2000).

[6]Limited time and resources prevented the committee from addressing the situation in the Pacific Fleet in any detail.

actor and assembly (critical and subcritical) selecting between reprocessing, long-term storage, and disposal for the SNF.

2.2 SPENT NUCLEAR FUEL IN THE UNITED STATES

As of December 31, 2001, the United States was storing approximately 45,000 MTHM (Holt 2002)[7] of spent fuel from its civilian nuclear power plants at reactor sites and at centralized facilities[8] (see Table 2.3) for eventual disposal in a geologic repository, and is producing new commercial SNF at a rate of about 2,000 MTHM per year. A smaller amount of spent fuel from the weapons program is also being stored for eventual disposal, but most has been chemically processed to recover plutonium, highly enriched uranium (HEU), or Np-237. The United States does not now reprocess its spent fuel from civilian nuclear power plants, so the current form of the SNF is the form that is to be disposed of in an underground geologic repository.

2.2.1 Power-Reactor Spent Nuclear Fuel in the United States

Production of nuclear power for civilian use and production of plutonium for nuclear weapons have mostly been separate in the United States.[9] Spent nuclear fuel from commercial power reactors (commercial SNF) constitutes the largest source and stockpile of SNF in the United States. This is due to the scale of the U.S. nuclear power enterprise (103 reactors generating 87.8 GWe

[7]DOE last updated its comprehensive inventory in 1999 (EIA 1999a), so information on the current inventory is scarce. The 1999 inventory provides the data for Table 2.3.

[8]Two centralized storage facilities—one in West Valley, New York, and another in Morris, Illinois—currently have SNF. Another has been proposed, called Private Fuel Storage (PFS), in Skull Valley, Utah. At West Valley, the fuel has been loaded into dual-purpose casks (storage and transportation) and awaits shipment to INEEL for interim storage.

[9]The most notable exception is the N-Reactor at Hanford, which produced more weapons plutonium than any other reactor in the United States, and also generated electricity. Some experimental reactors generated electricity for use by DOE facilities.

TABLE 2.3 Summary of Current Locations of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States[a, b] (*Denotes decommissioned reactors)

State	Commercial Reactors (MTHM in Storage)	Non-DOE Research Reactors	Navy Reactor Fuel	DOE-Owned Spent Fuel & HLW	Surplus Plutonium
Alabama	Browns Ferry 3 units (1,032); Farley 2 units (758)				
Arizona	Palo Verde 3 units (812)	University of Arizona, Tucson			
Arkansas	Arkansas Nuclear 2 units (730)				
California	Diablo Canyon 2 units (578) *Rancho Seco 1** 1 unit (228) *San Onofre* 1*,2,3 3 units (802) Humboldt Bay * 1 unit (28.9)	University of California, Irvine; General Electric (1 research, *2 research & test*, 1 power**); McClellan Air Force Base (now UC Davis); *General Atomics* *- MARK I** *- MARK F*;* Aerotest Research			
Colorado	Fort St. Vrain* (see DOE-owned fuel)	U.S. Geological Survey		Fort St. Vrain* (15.4)	Rocky Flats Environmental Technology Site
Connecticut	Haddam Neck* 1 unit (412) Millstone 1*,2,3 3 units (1061)				
Florida	Crystal River 1 unit (316) St. Lucie 2 units (715) Turkey Point 2 units (720)	University of Florida, Gainesville			
Georgia	Hatch 2 units (889) Vogtle 2 units (489)	Georgia Institute of Technology*			
Idaho		Idaho State University, Pocatello	Naval Reactors Facility (19.5)	Idaho National Engineering & Environmental Laboratory (INEEL) (273)	INEEL

TABLE 2.3, continued

State	Commercial Reactors (MTHM in Storage)	Non-DOE Research Reactors	Navy Reactor Fuel	DOE-Owned Spent Fuel & HLW	Surplus Plutonium
Illinois	Clinton 1 (207) Quad Cities 2 units (925) Braidwood 2 units (448) Zion 2 units* (1018) Byron 2 units (543) Dresden 1,* 2, 3 (950) LaSalle County 1, 2 (555) General Electric[c] (674)	University of Illinois, Urbana - Triga* - Lopra*		Argonne National Laboratory East (0.14)	
Indiana		Purdue University			
Iowa	Duane Arnold (301)	Iowa State University,* Ames			
Kansas	Wolf Creek (308)	Kansas State University (Manhattan)			
Louisiana	Waterford 3 (287) River Bend 1 (255)				
Maine	Maine Yankee* (542)				
Maryland	Calvert Cliffs 1, 2 (741)	University of Maryland, College Park; National Institute of Standards and Technology; Armed Forces Radiobiology Research Institute; U.S. Army Aberdeen Proving Grounds			
Massachusetts	Pilgrim 1 (362) Yankee-Rowe* (127)	Massachusetts Institute of Technology; University of Lowell; Worchester Polytechnic Institute			
Michigan	Enrico Fermi 2 (235) Cook 1,2 (885) Palisades (387)	University of Michigan (Ann Arbor)			

State	Commercial Reactors (MTHM in Storage)	Non-DOE Research Reactors	Navy Reactor Fuel	DOE-Owned Spent Fuel & HLW	Surplus Plutonium
Michigan (continued)	Big Rock Point* (58)	Dow Chemical Company (Midland)			
Minnesota	Monticello (193) Prairie Island 1, 2 (576)				
Mississippi	Grand Gulf (445)				
Missouri	Callaway 1 (359)	University of Missouri (Columbia) University of Missouri (Rolla)			
Nebraska	Cooper (233) Fort Calhoun (256)	Veterans Administration (Omaha)			
New Hampshire	Seabrook (172)				
New Jersey	Oyster Creek (438) Salem 1, 2 (625) Hope Creek (313)				
New Mexico		University of New Mexico (Albuquerque) White Sands Missile Range		Sandia National Laboratories -Annular Core Research Reactor -Sandia Pulse Reactor III (0.29)	Los Alamos National Laboratory
New York	Nine Mile Point 1,2 (656) Indian Point 1*, 2, 3 (757) Fitzpatrick (415) Ginna (311) Shoreham* (0)	State University of New York* (Buffalo) Cornell University -TRIGA Mark II -Zero Power* (Ithaca) Manhattan College* (Bronx) Rensselaer Polytechnic Institute (Troy)		Brookhaven National Laboratory, including -High-Flux Beam Reactor* -Brookhaven Medical Research Reactor (0.06); West Valley Demonstration Project[d] (26.8)	
North Carolina	Brunswick 1, 2 (486) Harris (693) McGuire 1, 2 (848)	North Carolina State University (Raleigh)			
Ohio	Davis-Besse (315) Perry (276)	Ohio State University (Columbus);			

TABLE 2.3, continued

State	Commercial Reactors (MTHM in Storage)	Non-DOE Research Reactors	Navy Reactor Fuel	DOE-Owned Spent Fuel & HLW	Surplus Plutonium
Ohio (continued)		National Aeronautics and Space Administration (Sandusky)*			
Oregon	Trojan* (359)	Oregon State University (Corvallis) Reed College			
Pennsylvania	Susquehanna 1, 2 (777) Limerick 1, 2 (634) Peach Bottom 2, 3 (1059) Three Mile Island 1 (346) Beaver Valley 1, 2 (521)	Pennsylvania State University; CBS Corporation (Waltz Mill)*; Saxton Nuclear Experimental Corporation (Saxton)*			
Rhode Island		Rhode Island Atomic Energy Commission			
South Carolina	Robinson 2 (153) Catawba 1, 2 (603) Oconee 1, 2, 3 (1,237) Summer (281)			Savannah River Site (67)	
Tennessee	Sequoyah 1, 2 (598) Watts Bar (39)			Oak Ridge National Laboratory (0.67)	
Texas	Comanche Peak 1, 2 (322) South Texas Project 1, 2 (448)	Texas A&M University (2) -AGN-201m -TRIGA (College Station) University of Texas (Austin)			
Utah		University of Utah (Salt Lake City)			
Vermont	Vermont Yankee (429)				
Virginia	North Anna 1, 2 (725) Surry 1, 2 (794) BWX Technologies, Inc.[e] Lynchburg (not at reactor storage)	University of Virginia* (2 reactors) (Charlottesville); Nuclear Ship Savannah, James River Reserve Fleet* (power)			

State	Commercial Reactors (MTHM in Storage)	Non-DOE Research Reactors	Navy Reactor Fuel	DOE-Owned Spent Fuel & HLW	Surplus Plutonium
Washington	Washington Nuclear Power 2 (302)	University of Washington (Seattle)*; Washington State University, Pullman		Hanford Reservation (2,132[f])	Hanford Reservation (Richland)
Wisconsin	Point Beach 1, 2 (582) Kewaunee (317) LaCrosse* (38)	University of Wisconsin at Madison			
Totals:					
Locations	118[g] (16 shutdown)	47 (9 shutdown)	1	11	6
Sites	72 (9 completely shutdown)	43 (6 completely shutdown)	1	10	6
Spent fuel in storage (MTHM)	38,310[h]			2,496	

[a] This table was adapted from (DOE 2000b).

[b] For commercial reactors, the quantities of spent fuel in storage onsite in 1998 are presented in parentheses in units of metric tons of heavy metal. Data are taken from EIA (1999a). These data are the most recent data available from the U.S. government. Revised data are planned to be published by the end of 2003.

[c] Commercial spent fuel storage site.

[d] SNF at West Valley is owned by DOE; West Valley High-Level Waste is currently owned by New York State Energy and Research Development Authority (NYSERDA).

[e] Fragmentary amounts of commercial fuel stored on site.

[f] From (DOE 2002a).

[g] Two away-from-reactor commercial SNF storage locations, i.e., Morris and BWX Lynchburg, not counted in these totals. The following reactors are considered to be co-located (i.e., at the same site): Fitzpatrick/Nine Mile Point; Hope Creek/Salem; and Indian Point 1, 2 and 3.

[h] Note that the total listed here is the total of the individual plants listed in the table, which differs from (EIA 1999a) totals in part because DOE owned commercial fuel is counted separately here.

on average during 2001 [EIA 2002]) and not having reprocessed fuel from power reactors since 1972.[10]

[10]Approximately 250 MTHM from commercial reactors were reprocessed at West Valley (DOE 1999a), although detailed records through the U.S. Energy Information Administration are only available on 94 MTHM of spent fuel from Dresden 1 and Humboldt Bay power plants (EIA 1999b). West Valley also reprocessed some SNF from plutonium-production reactors.

While there is little uniformity among the power-reactor designs, all but three of the reactors that have operated as commercial power reactors in the United States are either boiling-water reactors or pressurized-water reactors. The fuel elements in these reactors are zirconium-alloy tubes containing cylindrical pellets of ceramic UO_2, enriched to between 3 and 5 percent. The average burnup in batches of spent fuel discharged from these reactors ranges from nearly zero (for a reactor that shut down shortly after starting operations) up to approximately 45,000 MWd/MTHM. A small liquid-metal-cooled fast breeder reactor (LMFBR), called Fermi Unit 1 (61 MWe), operated in Michigan from 1966 until 1972. A small high-temperature gas-cooled reactor (HTGR), Peach Bottom Unit 1 (40 MWe) operated in Pennsylvania from 1967 until 1974. And a larger HTGR, the Fort St. Vrain Nuclear Generating Station (330 MWe), operated in Colorado from 1979 to 1989 and generated 24 MTHM of SNF in the form of prismatic graphite blocks containing silicon-carbide-coated microspheres of thorium carbide and highly enriched uranium carbide. The Fort St. Vrain fuel reached a burnup of about 39,000 MWd/MTHM (U.S. NRC 1999).

2.2.2 Government-Managed Spent Nuclear Fuel in the United States

DOE currently manages approximately 2,500 MTHM of SNF (see Table 2.4),[11] which is categorized as "materials-in-inventory" rather than as waste. DOE has over 250 different types of SNF in storage differentiated by isotopic and chemical composition, cladding, and geometry (DOE 2001b). This includes SNF from plutonium-production reactors, naval propulsion systems, test facilities, research reactors, experimental reactors, and demonstration reactors. The United States ceased reprocessing of plutonium-production reactor SNF for nuclear weapons in 1988. The "canyons" at the Hanford Site shut down in 1989. One of SRS's reprocessing canyons is used for processing unstable fuel. The Idaho Chemical Processing Plant (ICPP) ceased operating in 1992 (DOE 1992a).

As noted earlier, the United States has launched a total of 210 nuclear ships: 191 submarines with one reactor each, 9 aircraft carriers mostly with two reactors each, 9 cruisers with two

[11]DOE (2002a) reports 2,496.4 MTHM, whereas DOE (2001b) reports the mass of SNF in inventory as reported by DOE sites as 2,479.6 MTHM.

TABLE 2.4 Quantities of U.S. Government SNF and Unirradiated Nuclear Fuel Grouped According to Near-Term Management[a]

Near-Term Management	Quantity (MTHM)	Examples
Processed to HLW at ANLW	61.3	Sodium-bonded EBR-II and FFTF fuel
In foreign research reactors	14.3	HEU in Al plates in France, Pakistan, and four other nations
Storage until repository disposal (no further processing)	2,465	N-Reactor fuel, fuel from isotope production reactors, ANP fuel
Special treatment	0.041	Cutting fines from SNF assay, MSRE fuel
Processed to HLW at SRS	23.9	Declad EBR-II uranium metal fuel, declad uranium/thorium fuel
Treatment at ORNL Y-12 plant	0.27	Failed fuel from Rover[b]
Unknown	996	Unirradiated fuel for the N-reactor, FFTF, EBR-II
Unknown	25.2	Various fuel forms (unclad natural uranium, polyethylene matrices, aluminum) from test piles and research reactors, also unirradiated but damaged fuel (managed as spent fuel)

[a] All wastes are planned ultimately to be disposed of in a repository.
[b] Rover was a nuclear rocket prototype reactor with niobium-based fuel.
ANL-W: Argonne National Laboratory West
ANP: Aircraft Nuclear Propulsion
EBR-II: Experimental Breeder Reactor-II, at Argonne National Laboratory West
FFTF: Fast Flux Test Facility, at Hanford
MSRE: Molten Salt Reactor Experiment
ORNL: Oak Ridge National Laboratory
SRS: Savannah River Site
SOURCE: DOE (2002a).

reactors each,[12] 1 deep-submergence research vessel with one reactor (USNR 2001), and 1 civilian cargo ship with one reactor. All of the cruisers, the cargo ship, and 119 of the submarines have been removed from service (USNR 2001).[13] "Unlike civilian spent nuclear fuel which, after removal from the reactor, is currently

[12]The only exceptions were the submarine U.S.S. TRITON SS(R)N 586, which was launched with two reactors in 1958 and decommissioned in 1969, and the aircraft carrier U.S.S. Enterprise, which has eight reactors.

[13]The 119 submarines removed from service include 2 that were lost at sea and 2 that were converted to training platforms.

stored in plants around the country, all pre-examination naval spent nuclear fuel is shipped to one place, INEEL, for examination and temporary storage pending ultimate disposition…" (U.S. Navy 1996).

For over 40 years, "naval spent fuel has been shipped by rail in shielded shipping containers from naval shipyards and prototypes to the Expended Core Facility on the Naval Reactors Facility in Idaho where it is removed from the shipping containers and placed into water pools…" (DOE 1995). The pools are at the ICPP. "A total of approximately 65 metric tons (heavy metal) of naval spent nuclear fuel will exist by the year 2035." In 1996, DOE and the Navy decided to put the spent fuel at INEEL into dry storage using dual purpose canisters, which would serve both as storage containers at INEEL and as transport containers to a future repository (DOE 1996a). Until being shipped for disposal, these canisters are to be stored at the Naval Reactors Facility at INEEL (DOE 1997b).

"Naval nuclear fuel is designed to meet the stringent operational requirements for naval nuclear propulsion reactors….Current designs are capable of more than 20 years of successful operation without refueling….Measurements of the corrosion rates for naval fuel designs have shown that post-examination naval spent nuclear fuel can be safely stored wet or dry for periods much longer than …40 years…" (U.S. Navy 1996, pp. 2-3).

The Navy's program for decommissioned nuclear ships "involves defueling the reactor, inactivating the ship, removing the reactor compartment for land disposal, recycling the remainder of the ship to the maximum extent practical and disposing of the remaining non-recyclable materials." This takes place at the Puget Sound Naval Shipyard in Washington State. In 1984, the "Navy decided to dispose of the reactor compartments at the Department of Energy's Hanford site. The first reactor compartment was shipped…to the Hanford site for disposal in 1986….As of April 1999, the Navy has successfully shipped 79 reactor compartments to Hanford…" (U.S. Navy 1999). "With the ship in drydock…the fuel is removed into a shielded transfer container [and then] placed into specially-designed shipping containers" (p.3). The defueling process "removes over 99% of the radioactivity, and some small amount remains in the reactor plant after the nuclear fuel is removed [that] was created by neutron irradiation of the iron and alloying elements in the metal components during operation of the plant" (p.6). The ICPP reprocessed 44 MTHM of U.S. government

spent nuclear fuel (mostly naval fuel) between 1953 and 1992 to recover highly enriched uranium (NRC 1999b). The ICPP was renamed the Idaho Nuclear Technology & Engineering Center in 1998, and the facilities are currently used to store spent nuclear fuel and radioactive waste, treat radioactive waste, and develop waste management technologies. After the submarine reactor compartment is cut out and removed from the hull, shipyard fabricated bulkheads are welded to the ends. For cruisers, a complete package is fabricated for the reactor compartment. The compartment is loaded on a barge and sent to Hanford.

Some of the experimental reactors used exotic fuels, such as nickel-alloy fuel from the Aircraft Nuclear Propulsion Program and molten-salt fuel from the Molten Salt Reactor Experiment (MSRE).

In the 1970s in the United States, as many as 70 research reactors were operated by universities and dozens of research and test reactors were operated for government and private research. Today, 36 civilian (non-DOE and non-military) research reactors operate and 13 are in the process of decommissioning (one of these is a small power reactor) (U.S. NRC 2002b). The thermal output of these reactors ranges from 0.10 watt to 20 megawatts. Several reactors are operated by the DOE national laboratories and the military in the United States. In addition, the United States has provided fuel for 110 research reactors in other countries (DOE 2002a). The United States has a program to take back highly enriched uranium fuel from these foreign research reactors. Much of the highly enriched foreign research reactor fuel has been returned to the United States and resides at SRS and at INEEL, but approximately 2.7 MTHM of highly enriched fuel of U.S. origin are still at research reactors in over 30 nations (including small amounts in Iran, Israel, Pakistan, and the Philippines). It is hoped that these will return to the United States (DOE 2002a), along with the approximately 11.6 MTHM of fuel with initial enrichment of 20 percent or less.

DOE also has 998.3 MTHM of unirradiated fuel, 2.3 MTHM of which are managed as SNF because they are damaged. Over 95 percent of the unirradiated fuel is N-Reactor fuel at Hanford that was not fully finished in the fabrication process or that was finished and loaded but never irradiated in the reactor. Disposition paths have not been selected for these unirradiated fuels, although they may ultimately be treated as waste. The DOE SNF and unirradiated fuel mentioned above together with the approximately 22.9 MTHM of contact-handled SNF that has no assigned

disposition path (most of this is lightly irradiated material from a test pile at SRS) constitute the total 3,518.22 MTHM of nuclear fuel DOE currently manages. DOE approximates it will have another 67 MTHM from naval and research reactors by 2035.

DOE plans to treat or chemically process fuel that is not suitable for disposal in its present form. Much of this SNF is from government sources, but some is from commercial reactors. Treatment includes activities such as vacuum drying the N-Reactor spent fuel that is sitting in the storage pools. Fragments and sludge from N-reactor fuel (some of which is badly corroded) may be shipped for disposal at WIPP.

Processing converts the highly radioactive constituents of the SNF into high-level waste. Aqueous chemical processing will be carried out at SRS's Canyons for what is termed "at risk" fuel—fuel that is damaged or corroded. Argonne National Laboratory West will use electrochemical processes developed there to process sodium-bonded SNF (SNF made with liquid metal in the gap between the fuel and its cladding to facilitate heat transfer). The different disposition paths and examples of the SNF associated with these paths are presented in Table 2.4.

2.3 DISPOSITION OF EXCESS WEAPONS PLUTONIUM

Disposition of excess weapons plutonium is connected to this study because the options for disposition include processing that would lead to managing the material as SNF or HLW.

As thousands of nuclear weapons are dismantled under the Strategic Arms Reduction Treaties (START I and II) and under initiatives by both the United States and the Russian Federation, tens of metric tons (MT) of weapons-grade plutonium and hundreds of metric tons of highly enriched uranium have been declared surplus to the needs of each nation's military program. The surplus material poses a security risk because of the possibility it might be stolen and used to construct a nuclear weapon. As a beginning, the U.S.-Russia Plutonium Management and Disposition Agreement (PMDA), signed in September 2000, states that each nation is to dispose of 34 MT of surplus defense plutonium. This agreement does not cover all of the plutonium each nation has declared excess to defense needs, but it is a first step.

Russia and the United States have been working on finding disposition paths that are technically sound and that satisfy de-

mands driven by domestic policy and international relations. From the outset, Russia has expressed its desire to fabricate plutonium-uranium mixed-oxide (MOX) fuel with the excess material, and to irradiate that fuel in existing VVER-1000 reactors and its BN-600 reactor, although Russia would prefer to use the fuel in a future BN-800. The United States has been less consistent in its planning.

The United States began assessing alternatives for plutonium disposition in 1992 when the federal government asked the National Academy of Sciences to carry out a study of the management and disposition options available (NAS 1994). Following that study, DOE's laboratories examined dozens of technologies for plutonium disposition. DOE announced in January 1997 its intention to pursue a dual-track disposition strategy: (1) fabricating the clean plutonium into MOX fuel and irradiating that fuel in existing domestic reactors (approximately 26 MT of plutonium); and (2) immobilizing the impure plutonium, which was deemed unsuitable for MOX fuel, in a ceramic waste form encased in vitrified HLW (approximately 8 MT of plutonium).[14] This decision was reaffirmed in 2000, but in 2001, the new DOE leadership announced that the existing plan would take too long and be too expensive. After a review of the options, DOE decided to eliminate the immobilization program and only pursue the MOX option. DOE concluded that 6.2 MT of the 8 MT of impure plutonium could be processed by aqueous polishing in a new facility to be constructed at the front end of the MOX fuel-fabrication plant at SRS, after which the material would be suitable for MOX. This still leaves 1.8 MT from the U.S.-Russia agreement that must go into the disposition program, and these are to be made up by future declarations of surplus material. The actual quantity of impure plutonium (often referred to as "dirty" plutonium) that DOE manages and how the plutonium is to be disposed of have not been made clear. Finding a disposition path for the impure plutonium is not a trivial task because, most likely, it is not currently in a form that is suitable for disposal. Developing a disposition path will require a clearer picture of the technological options available, which in turn depends on having a clear picture of the quantity and character of the material.

[14]There is a program of cooperation between the United States and Russia on disposition of excess weapons plutonium. The program, funded through the Lawrence Livermore National Laboratory, covers waste form development as well as plutonium storage, packaging, and transportation; spent fuel storage, packaging and transportation; and treatment of plutonium-bearing wastes. See Jardine and Borisov (2002).

Current DOE plans are to complete designs for the MOX fuel-fabrication facility in 2003, to complete construction in 2004, to complete the licensing by the 2005, and to begin hot startup of the facility in 2007. The first MOX fuel would be loaded into a reactor in August of 2008 and full scale operations would run from 2009 through 2019.[15] The U.S. Congress has indicated that progress through this schedule is contingent upon progress on similar efforts in the Russian Federation, because the programs are coupled to a negotiated agreement. At the same time, from a technical perspective, this is an ambitious schedule, particularly since there is not yet a decision on how to manufacture the "lead test assemblies" (the first trial fuel assemblies) so that they can be tested and licensed for use in a commercial reactor, and because one of the two utilities that had originally signed up for the MOX program has pulled out. While this will not be the first MOX fuel in U.S. light-water reactors (see Cowell and Fisher 1999, Chap. 3), the United States does not have any recent operational experience with MOX fuel in power reactors. Further, the composition of the Pu is different. DOE will need a plan for manufacturing the lead test assemblies and will need that plan soon if it is to keep to a schedule close to the one it put forward.

Making progress on the materials-disposition program is important to both countries, but steady progress will be difficult without clearer plans.

2.4 END POINTS

As defined in Section 1.3, the committee differentiates between interim and final end points. All methods of treating spent nuclear fuel and radioactive waste lead to some highly radioactive material that must be sequestered at least for many centuries. A recent report from the National Research Council (2001a) concluded that the only final method of sequestration that would not require continual monitoring and funding is geological disposal. However, local political difficulties have made developing such sites difficult. Adhering to the process established in the law governing disposal of HLW in the United States (NWPA 1982), the U.S. Congress voted to override the state of Nevada's veto of

[15] The current schedule was provided by Kenneth Bromberg, program integration director for the Plutonium Disposition Program at DOE, in a conversation with staff on December 20, 2002.

President Bush's decision to pursue a repository at Yucca Mountain. It was unclear until the time of the vote (July 9, 2002) whether the override effort would succeed. In addition, even if a geological repository is developed, there will be large amounts of HLW and SNF that must be stored and protected for decades before a repository will be ready to accept the material.

The United States has large amounts of HLW from nuclear weapons programs and large amounts of SNF, primarily from operation of commercial reactors to generate electricity. As discussed in other sections, the defense waste is stored in tanks, some of which have leaked and many of which have waste mixtures that are poorly characterized. Two of the tanks at SRS have been emptied and closed. Until recently, the DOE program was to do the same with all of the other tanks, that is, remove all these wastes, immobilize them (specifically to vitrify them, although other immobilization technologies are under examination), store the immobilized waste, and then ultimately send the product to the geological repository expected to be developed. In this past year, the Environmental Management Office of the DOE reviewed its program and stated its intent to accelerate the cleanup of the defense sites. DOE has entered into agreements with regulators at the sites to consider alternative ways to manage the wastes and accelerate cleanup, which may include leaving some waste at the sites (e.g., stabilized by grouting tank sludge in place).

Commercial SNF has been stored at the reactors in pools and after pools get filled, in dry casks. The final end point is to be the geological repository.

Russia has chosen to reprocess most of its SNF using the "closed" fuel cycle. As in the United States, the final end point for HLW is planned to be geological repositories of vitrified waste located, however, at the reprocessing sites. Later sections discuss the programs in Russia to find appropriate interim and final sites. The Russian program has used phosphate glass, unlike the United States, which uses borosilicate glass. However, experimental studies (Zotov et al., 1996) have shown that aluminum-phosphate glass is unacceptable for long-term isolation required for HLW and can be used only for immobilization of short- and medium-lived radionuclides. Nevertheless, this form of HLW vitrification is safer than storage of HLW in a liquid form. Studies are being carried out on synthesis of glass-crystalline waste forms for HLW that are a few orders of magnitude more durable against leaching than aluminum-phosphate glass is (Matyunin 2002; Rovny et al. 2002).

2.5 FUEL-CYCLE STEPS AND END POINTS FOR SPENT NUCLEAR FUEL

Nuclear fuel cycles can be constructed from a small number of fuel-cycle steps, arranged and repeated so as to achieve the desired result. These steps include production of fissile material (through enrichment or through recovery from processed irradiated fuel), fuel fabrication, storage, transportation, irradiation in a reactor, reprocessing, and disposal. The storage and disposal steps are discussed below in the context of end points.

In the closed cycle, the SNF is reprocessed (the current preferred term of the nuclear industry is “processed”) to separate out the large amount of remaining uranium and the plutonium that was produced during reactor operations. The short half-life isotopes that are the principal sources of both heat and radioactivity (Cs and Sr) are separated in another stream while still further separation can be done for other fission products. Fuel cycles can, to some extent, be tailored to change or reduce waste streams (see Sidebar 2.1), but while the duration and technology needed for the fuel-cycle steps might change, the need for storage and disposal cannot be eliminated.

2.5.1 Storage of Spent Nuclear Fuel[16]

Spent-fuel-storage technologies are generally designed to prevent releases of radionuclides, exposure of workers, and theft or loss. Radioactive decay within the fuel and criticality events can cause both releases, resulting from overheating, and direct worker exposures, if SNF is not stored properly. Some SNF is a potential target for theft, because the fissile and other radioactive constituents could be used to construct a nuclear or radiological weapon.

The technology for interim storage of SNF in surface facilities is well established, and generally falls into one of two categories: wet storage or dry storage. Wet storage uses water to cool the SNF and to shield against penetrating radiation. Because of cooling demands, SNF freshly removed from a reactor typically needs to be stored in a cooling pool. Cooling pools are typically steel reinforced concrete structures with stainless steel or epoxy liners. The pool may be covered or open to the air, but any cover

[16]A recent report by Bunn et al. (2001) describes different aspects of interim storage of SNF.

SIDEBAR 2.1: Transmutation

> "Any intense source of neutrons, such as a …fast reactor…or an accelerator-driven subcritical reactor, can accomplish transmutation of long-lived radionuclides. The physical requirements for neutron intensity and the energy requirements to achieve such intensity make it necessary to partition, or separate, the long-lived radionuclides to be transmuted from the uranium, the fuel rod cladding and other components in SNFand HLW. Partitioning is essentially the same as reprocessing spent fuel to recover plutonium and uranium..." (NRC 2001a, pp. 119-120).

This approach has been discussed for several years, and was summarized in a 1999 NEA report.

> "An approach that has been claimed to have the potential to change the future of geological disposal is partitioning and transmutation (P&T) of long-lived radionuclides to give wastes which have shorter half-lives and therefore do not present as serious a challenge to the isolation capacity of repositories" (NEA 1999a).

At the request of the U.S. Congress, DOE has studied the potential of accelerator transmutation of waste (ATW). A DOE report (1999b) concluded:

- There would be benefits in reduction in long-term radiation doses from the HLW stream.
- "[A] repository is still required due to the presence of defense wastes, which are not readily treatable by accelerator transmutation of waste, and the long-lived radioactivity generated by ATW operations."
- The report proposed a six-year $280 million R&D program.
- If the R&D were successful, an additional $280 billion would be necessary, with the program lasting a century.

A previous National Research Council study (1996a) on separations and transmutation also concluded that the need for a geologic repository would not be eliminated by transmutation, and that repository doses could be reduced by transmutation (particularly for intrusion scenarios), although the changes in doses would be small, particularly when the whole fuel cycle is examined.

A recent paper by Lowenthal (2002) notes that "transmutation can be described as reducing disposal inventories by increasing current

continues on next page

Handling and operations." This presents several tradeoffs regarding types of hazards: radiological, safeguards and proliferation, and criticality.

Both the United States and Russia are investigating partitioning and transmutation. The United States is doing so in the Advanced Fuel Cycle Initiative and Russia in its on going examination of fuel cycles involving fast reactors and reprocessing spent nuclear fuel.

must be removable so as to allow for an overhead crane to maneuver the fuel assemblies and any containers in which they are stored. The water is actively cooled by pumping it through a heat exchanger. The racks that hold fuel assemblies in spent fuel pools are configured to prevent criticality and, if the geometry itself is insufficient, plates loaded with boron are placed between the assemblies or boric acid is added to the water to absorb neutrons. The water chemistry is actively controlled to maintain the boron concentration in the water, to reduce the rate of corrosion of the fuel cladding, and to remove radionuclides that might have leaked through failed cladding.

Dry storage can be in vaults, silos, or casks[17] and relies on air or inert gases (such as nitrogen, or helium) to provide cooling. Dry storage is most appropriate for SNF that is past the initial period after removal from a reactor when its heat-generation rate is highest. In most dry storage designs, the spent fuel assemblies (SFAs) are sealed in an inert atmosphere inside a steel canister that is welded shut.

Vaults are typically concrete structures with many compartments to hold the canisters. The canisters prevent release of radioactive dust and volatile fission products and protect the fuel from chemical reaction. Cooling is accomplished by either forced or natural air convection around the canisters and biological shielding is provided by the concrete structure. Vaults generally rely on geometry to prevent spontaneous chain reactions (criticality events).

Silos are concrete cylinders that serve as sleeves for canisters, emplaced either vertically or horizontally, providing shielding and physical protection for the fuel. Vertical silos typically ac-

[17]The translation of the Russian terminology to English results in vaults being referred to as chambers and silos as reinforced concrete massifs. Rather than adopt one over standard usage over the other, the standard terminology is kept and the difference is noted.

commodate several canisters in one concrete cylinder. Silos rely on passive convective airflow along the outside of the sealed canisters to provide cooling, and so have holes for inlet and outlet of the air. Silos are constructed on a concrete pad.

Dry storage casks are combined systems that provide shielding and prevent releases of radioactive materials and are moved as integral units. Spent fuel assemblies can be loaded directly into the casks, which are typically made of steel or steel-reinforced concrete with a steel liner. The limited number of assemblies in each cask or silo, and the lack of water acting as moderator surrounding the SNF reduce the concerns about criticality (unless the fuel is highly enriched). Borated steel plates are still, nonetheless, commonly used as a safety measure, particularly for casks that are loaded under water. Some casks can be used for both transportation and storage (dual-purpose casks).

Both wet storage and dry storage have excellent safety records, although there is the potential for storage pools to lose their water as a result of leaks, and thereby lose their shielding and cooling.

Dry storage has increased in popularity among reactor operators as demand for storage capacity beyond that available in the at-reactor storage pool has increased. In these cases, older fuel can be loaded into dry storage. Both the initial capital costs and the continuing operating costs of dry storage are lower than for wet storage.

Some forms of storage, such as interim storage in the reactor compartments of decommissioned submarines, storage in maintenance vessels, and storage in the open air, are undesirable. These are not safe and secure forms of storage, so they are not appropriate end points, interim or final.

Storage of Spent Nuclear Fuel in Russia

In Russia, cooling pools at nuclear power plants are designed, as a rule, for a three-year storage period during which the heating from radioactive decay drops dramatically (e.g., by a factor of nearly 12,000 for VVER-1000 SNF). Then the fuel is transported for reprocessing or interim storage. Spent fuel from VVER-440 reactors and the BN-600 reactor is sent for reprocessing to the RT-1 plant at PA “Mayak,” where it is stored in a large pool until it is chopped up and reprocessed in the plant.

More than 8,700 MTHM of RBMK SNF with total radioactivity of 3.1 billion curies are stored in cooling pools at the power plants and at separate wet-storage facilities onsite. At the Leningrad Nuclear Power Station, for example, fuel is stored for three to five years in the cooling pool adjacent to the reactor building, then is loaded into a cask full of water and moved to a storage building nearby on the site (NAS 1990). Approximately 3,000 fuel assemblies are breached, which complicates handling and storage.

Dry storage is expected to replace pool storage for all of the fuel in coming years. It is anticipated that the roughly 8-meter-long RBMK fuel assemblies will have to be cut in two to fit inside the dry storage casks. Russia does not currently ship any RBMK SNF, with the exception of transportation of half-assemblies for post-reactor tests in hot cells.

The decision on the long-term plan for RBMK fuel management has not been made yet. Several approaches are possible and are now under consideration. Although accumulation of RBMK SNF at the power plant site can lead to difficulties when the plant is to be decommissioned,[18] this spent fuel is not seen as a proliferation or an immediate health hazard, so it is the committee's judgment that leaving it in place is a reasonable allocation of scarce resources. Nevertheless, to prevent theft for possible use in a radiological weapon, this spent fuel must be protected at the sites.

At present, approximately 1,500 VVER-1000 fuel assemblies (about 680 MTHM) with total activity of 600 million curies are stored in cooling pools at the power plants, which are about 40 percent full. In addition, there is a centralized wet-storage facility for VVER-1000 fuel at the Krasnoyarsk MCC. This centralized facility has a storage capacity of 15,000 fuel assemblies (about 6,000 MTHM), which is about 37 percent filled today. Moreover, an unfinished part of the facility has a capacity of up to an additional 3,000 MTHM. The VVER-1000 SNF cannot be reprocessed at RT-1 unless upgrades are made to one of the process lines. The RT-2 plant that was planned to be built at the Krasnoyarsk MCC was designed to process VVER-1000 SNF and other fuels. Some structures were built for RT-2 before the project was halted for lack of funds, and these are now being adapted for storage. Once modernized, the facility capacity will be increased up to 9,000 MTHM. About 50 breached VVER-1000 fuel assemblies are

[18]In particular, a tariff on nuclear power plant operations provides funds for management of SNF. These funds are not available after decommissioning.

currently stored in separate sections of the pools at the power plants, and are planned to be shipped to RT-1 by 2007. There are now plans to construct a wet-storage facility with a capacity of 1,700 MTHM at PA "Mayak."

The SNF from the Beloyarsk nuclear power plant was unloaded and kept in dry storage at the site (190 MTHM of SNF in 5,000 fuel assemblies) and in the PA "Mayak" cooling ponds (76 MTHM of SNF in 2,200 fuel assemblies). Most of these fuel assemblies are breached. The Bilibino power station has accumulated 164 MTHM (6,500 assemblies) of SNF, none of which are breached. Some of this SNF has already been transferred to a dry storage facility at the power plant site.

As mentioned above, Minatom is currently considering adding new dry-storage facilities using the uncompleted buildings at the site of RT-2. The facility would be financed by Rosenergoatom. A decision has been made that it should be a vault-type (chamber-type) storage facility with a capacity of 33,000 MTHM. To provide interim RBMK SNF storage at the power plant sites, dual-purpose casks, the TUK-104 and TUK-109 with capacities of 114 and 144 irradiated half-assemblies of RBMK-1000 fuel, have been developed. The same casks can be used to transport SNF to a centralized facility.

Russia is studying the condition, possible degradation modes, and maximum thermal loads of its irradiated SNF in order to develop its dry-storage capabilities. In particular, studies focus on the condition of structural materials in irradiated fuel assemblies that have been in wet storage, and on how these materials might degrade in dry storage. Quantitative models for assessing the thermal conditions and material behavior are being developed so that appropriate storage regimes (temperatures, environment, etc.) can be selected.

Spent nuclear fuel from the Northern Fleet's NPSs that has not yet been shipped for reprocessing at PA "Mayak" is currently stored in shore technical bases at Andreeva Bay and at the Gremikha settlement, as well as in storage tanks of floating technical bases (FTBs), and on board decommissioned NPSs. A technical base is a facility for servicing, fueling and defueling, and decommissioning and dismantling of nuclear-powered submarines. In 1998, there were about 8,300 SFAs of reprocessible SNF stored at naval FTBs, NPSs that await defueling, and FTBs for the nuclear-powered ice-breaker fleet. The total of defect fuel, which is unreprocessible, at coastal technical bases was about 4,400

SFAs. The problems associated with storing the cores from nuclear-powered submarines are mostly due to the lack of needed infrastructure (i.e., lifting and transport facilities, coastal structures, and interim regional storage facilities that are insufficient both in number and in capacity). But it is also true that many of the SFAs in storage and the storage facilities themselves, particularly the FTBs and NPSs, are in very poor condition and constitute serious hazards.

Andreeva Bay hosts the largest SNF-storage facility in the region. The facility operated a storage pool until 1983 when, as a result of the poor condition of the facility, it was decided to construct a temporary facility for short-term (three to four years) dry storage and to transfer the stored SNF to this new facility (Bøhmer et al. 2001; Nilsen et al. 1996). The short-term storage facility has been in operation for over 18 years. The facility is now full, but it would not be able to accept new SNF in any case because of structural shortcomings and because the facility does not comply with current safety requirements (Bøhmer et al. 2001; Ivanov et al 1999). A total of 21,640 SFAs are stored at the shore technical base at Andreeva Bay, including 220 SFAs that are stored in containers that sit in an open area (not enclosed in a building) (Bøhmer et al. 2001).

The Gremikha settlement hosts the Northern Fleet's second largest storage facility for SNF. The facility was planned to store SNF from light-water reactors of the first generation of NPSs and spent retrievable elements from NPSs with liquid-metal-cooled reactors.

The storage facility consists of drained cooling ponds (100 SFA), containers in an open-air site (700 SFA), and a concrete shaft for retrievable elements of reactors with liquid-metal coolant (6 units). The facility is in a generally poor state.

At present, two Project 2020 FTBs (Malina class service ships) are the only ones available in the Northern Navy and capable of executing all of the steps from unloading of SNF from NPS reactors to transferring the fuel for railway transport (Ivanov et al. 1999). One FTB is at the shore base in Olenya Guba (Kola Peninsula) and the other one is in the area of Severodvinsk (Arkhangelsk region). Each FTB has tanks in which operators store containers of SFAs. The number of SFAs that a tank holds depends on the characteristics of the SFAs, but each FTB can store the SNF from two NPSs (Ivanov et al. 1999). The actual inventory at

any given time varies depending upon the refueling, defueling, and storage demands.

The civilian ice-breaker fleet of the Murmansk Shipping Company has three of its own FTBs, which store the fleet's SNF. The ships are Imandra, Lotta, and Lepse. All of these FTBs are moored at the Repair-Technological Enterprise "Atomflot." The storage tanks on Imandra can accommodate up to 1,530 SFA, or about 6 cores from the ice-breaker reactors (Bøhmer et al. 2001; Nilsen and Bøhmer 1994). Imandra has also been used to defuel NPSs from the Navy (Bøhmer et al 2001). Lotta uses dry storage to accommodate as many as 4,080 SFAs loaded into containers, although some of that total is devoted to unreprocessible SFAs that are stored until a disposition path is found (Bøhmer et al. 2001; Nilsen and Bøhmer 1994). Lepse, the oldest of these FTBs, was used until 1980 for reloading of nuclear fuel and for storage of fresh and spent nuclear fuel from nuclear-powered icebreakers Lenin, Arktika, and Sibir. Lepse, unlike the other FTBs, stores each of its approximately 640 SFAs in a separate cell. The cell cannot be removed without disturbing the ship's structure. All of the SNF on Lepse is over 20 years old, and although the cells were filled with water during earlier operations, the SFAs are now stored dry. During the years of wet storage, the SFAs corroded enough to change their geometry and now cannot be removed from the cells, so all of Lepse's SFAs are deemed "non-retrievable" (Ruzankin and Makeyenko 2000; Safutin et al. 1999). Lepse was decommissioned in 1988 and moored in place in 1990. In 1991, in order to provide additional shielding, the space between the SNF storage tanks was filled with special concrete mixtures (Bøhmer et al. 2001).

About 60 decommissioned NPS containing roughly 26,000 SFAs (as of 2001) sit floating near the coastal bases and await defueling (Bøhmer et al. 2001; Sinisoo 1995; Alekseyev 2001). This is the equivalent of about 110 cores. Decommissioned NPS are not well prepared to sit afloat for long periods without regular maintenance (Ruzankin and Makeyenko 2000), and the older ships (those that have sat for over 10 years), which total roughly 30 (Atomic Chronicle of Russia 2000), pose the greatest potential radiological hazard. Because of the much higher enrichment in maritime fuel compared with power reactor fuel, this SNF must be included in a MPC&A program.

Plans have been developed for a repository for interim storage of SNF from NPSs and for disposal of other nuclear materials on the Kola Peninsula.

Storage of Spent Nuclear Fuel in the United States

The majority of U.S. SNF is that generated at commercial power reactors. Most of this SNF is stored at the generation sites, either in pools or in dry-storage casks. As of December 31, 2001, there were 3,000 MTHM of spent fuel in dry cask storage and 42,000 MTHM in pool storage, for a total of 45,000 MTHM (Holt 2002).

Sixteen power-plant sites and two DOE facilities are licensed by the U.S. Nuclear Regulatory Commission for dry-cask storage (U.S. NRC 2001). Each kind of dry storage facility—vaults, silos, and casks (chambers, reinforced massifs, and casks)—has been built in the United States (Bunn et al. 2001). Some SNF, particularly from older reactors, was shipped for storage offsite at independent spent fuel storage installations in Illinois at the Midwest Fuel Recovery Plant (674 MTHM) and in New York at the West Valley Demonstration Project (26 MTHM). Some SNF seen as special cases are stored in Idaho at INEEL (171 MTHM and at other DOE facilities (26 MTHM) (DOE 2002a). Several older commercial reactors had their SNF reprocessed at West Valley, and a small amount was reprocessed at SRS.

Some DOE-managed SNF is undergoing modest treatment to allow for safe storage, packaging, and disposal. Nearly 85 percent of this set is spent fuel from the N-Reactor at Hanford, some of which is highly corroded. Most of the irradiated N-Reactor fuel (roughly 2,100 MT containing 4 MT of plutonium, 105,000 assemblies, amounting to 55×10^6 Ci) is stored in the K-East and K-West Basins (cooling pools) along with a small amount (974 fuel elements) of SNF from the older reactors at Hanford (Gerber 2001; DOE 2000c). N-Reactor fuel is solid uranium metal with zirconium-alloy cladding, and the SNF in the K-Basins has been stored for 15 to 31 years. The SNF from the older “single-pass” reactors is aluminum-silicon clad. Some of the N-Reactor SNF was damaged (breaks in the cladding) during discharge and, over the years, water has seeped in and oxidized some of the fuel, causing it to swell and damage the cladding. The oxidized fuel sloughs off and accumulates as sludge in the canisters. The SNF has been visually inspected and the following assessment found in DOE (2000c, DOE 2002b) was made (see Table 2.5).

“Intact fuel” has no evidence of cladding breach of deposited sludge; “breached fuel” has minor cladding ruptures with no

TABLE 2.5 Assessment of Fuel Stored in the K Basins

Damage Category	K West Basin	K East Basin
Intact fuel	50%	49%
Breached fuel	39%	9%
Defected fuel	0%	38%
Bad fuel	11%	4%

SOURCE: DOE (2002b).

reacted fuel or deposited sludge visibly present; "defected fuel" has definite evidence of cladding breach with reacted fuel escaping as oxide or sludge from the element; and "bad fuel" has gross cladding failure with substantial element dilation, clad splitting, element deformation, or fuel void.

Exposed fuel has contaminated the water in the pools. The SNF in the K-East Basin (51,000 assemblies) sits in 3,700 canisters that have no caps, so one or both ends of the canisters allow free flow of water. The K-East Basin walls and floors were not sealed before the fuel was loaded into the pool and water has leaked on two occasions: releasing approximately 5.4×10^4 m^3 of contaminated water into the subsurface through a floor joint in the late 1970s, and releasing about 340 m^3 in 1993 (Gerber 2001). The walls of the K-West Basin were coated with sealant and the cans in that pool are capped, so fewer problems are anticipated in treating that fuel.

Treatment of the fuel involves several steps to be carried out under water: removing canister lids (if they are present), cleaning the fuel to remove corrosion products, loading the fuel into baskets and placing the baskets in a single 14-foot long, 2-foot diameter multi-canister overpack. The baskets are configured to prevent criticality, and specialized copper baskets have been designed to hold fuel scraps ranging from fines up to 3 inches across. (As of December 2002, the project had accumulated nearly 6 tons of fines.) The fuel is then dried, which is accomplished by cold vacuum drying. The canister is then shipped to a vault-type storage facility made of steel reinforced concrete. The storage facility will hold 400 of the multi-canister overpacks in 220 steel tubes that extend 12 meters below the facility floor. Passive cooling is provided by convective air flow (Gerber 2001). As of December 2002, 167 multi-canister overpacks had been loaded and all but 2 were in the storage facility. The fuel is to be stored for 40 years, or until a repository is available to accept the fuel for disposal.

About 50 cubic meters of sludge with varied composition (uranium oxides and hydrides, cladding debris, and various corrosion products) has accumulated on the K-Basin floors, in the canisters, and in the basin pits. Over 80 percent of the sludge is in the K-East Basin. The current plan for this material is to package it and store it until a disposition path for the material is identified.

The program to process the N-Reactor fuel and place it in dry storage had an ambitious schedule. All of the fuel was to be processed by the end of 2003. Early milestones were missed, but DOE has now treated most of the fuel from the K-West Basin and has transferred some of the fuel from the K-East Basin and treated it for storage. The committee notes that progress is being made on the K-Basin fuel, but thus far the program has only addressed the fuel that is in better condition. The more difficult work, dealing with the most damaged fuel in the K-East Basin and the fines and sludge, is still ahead.

Other SNF, such as aluminum fuels from research reactors around the world and production reactors within DOE, require some kind of treatment to make them safe for storage and disposal. Workers at SRS, where DOE is gathering and storing the research reactor fuel, are developing a “melt and dilute” technology for the highly enriched aluminum SNF, termed “at risk” SNF because of security and criticality concerns. The sodium-bonded SNF from the Experimental Breeder Reactor-II is being treated using electrometallurgical processes (also called pyroprocessing) in an experimental apparatus at the Argonne National Laboratory West (DOE 2000d).

DOE manages batches of fuel that must be treated as special cases. The most dramatic example that has already been treated is the 81.5 MTHM of fuel and fuel debris from the Three Mile Island (TMI) plant’s Unit 2 reactor, which underwent a partial core melt during an accident on March 28, 1979. Some of the fuel elements are in good condition, but others melted into a mixture of the fuel, cladding, control rods, burnable poisons, and other reactor components. Nearly all of the fuel and fuel debris from the accident is stored at INEEL, where it is being dried and transferred from pool storage to the TMI Dry Storage Facility. This fuel and fuel debris is currently planned to be disposed of in a geologic repository along with other spent fuel. Other fuel that has not yet been processed or treated includes fine particles from cutting SNF inside hot cells for assay, and the MSRE fuel, which is no longer molten.

2.5.2 Disposal of Spent Nuclear Fuel and HLW

The United States currently plans to dispose of commercial spent nuclear fuel directly, without chemical processing. The fuel assemblies are to be loaded into metal canisters, sealed, and shipped for disposal in a mined geologic repository. Under the Nuclear Waste Policy Act of 1982, the federal government is supposed to take title to this fuel and put it into a geologic repository. DOE is responsible for the disposal of commercial and defense SNF, as well as other HLW. To fund the commercial SNF portion of this program, a tax of 0.001 dollars per kilowatt-hour is placed on the electricity sold by each nuclear power station[19] and some government funds have been appropriated from defense programs to cover approximately one-third of the program costs to date. It is this funding that has been used to investigate the Yucca Mountain site, in Nevada, as a possible location for the first HLW repository (see Sidebar 2.2).

After two decades of study by the Department of Energy, the President of the United States approved the department's proposal to apply to the Nuclear Regulatory Commission for a license to construct a repository at this site. The governor of the state of Nevada vetoed the proposal, but the United States Congress overrode that veto. The official DOE program plan is to submit a license application by December 2004. The U.S. NRC would then take three years (possibly four) to review the application and to decide whether to grant authorization for construction. DOE hopes to have construction authorization by the end of 2007 and to open the repository in 2010. Most external commenters believe this ambitious schedule is unrealistic based on the time needed for each step. In addition, several lawsuits that attempt to block the various steps in the process have been filed. The spent fuel will sit in some form of interim storage until a repository is available.

The generators of the commercial SNF have historically been responsible for the costs of storing the SNF prior to disposal, but as schedules for disposal of the SNF are pushed into the future, lawsuits have been filed demanding that DOE cover the costs. Courts are in the process of deciding on these lawsuits.

[19]Only about half of the tax collected has been used for the disposal program, with the rest put into the U.S. Treasury for general purposes.

SIDEBAR 2.2: The Planned Repository at Yucca Mountain

Yucca Mountain is located about 160 kilometers northwest of Las Vegas, Nevada, at the western edge of the Nevada Test Site (where testing of nuclear weapons was carried out). The area surrounding the site is sparsely populated and receives an average of 17.0 centimeters of precipitation per year. The mountain is made up of a volcanic ash, called tuff, which was deposited approximately 12 million years ago. The mountain has been under investigation for over 20 years as a potential host for the first mined geologic repository for spent nuclear fuel and high-level radioactive waste (HLW) in the United States, and the Congress has given approval for DOE to proceed with a license application to construct the repository. The proposed design would place the repository in a layer of welded tuff in the unsaturated zone, approximately 300 meters below the surface and approximately 300 meters above the water table (i.e., above the saturated zone).

The current design for the potential repository calls for spent nuclear fuel and high-level radioactive waste to travel to Yucca Mountain by truck or rail in shielded shipping containers. DOE has done only preliminary transportation studies, explicitly avoiding more detailed planning until after the site recommendation, which occurred in 2002. Once these materials arrive at the repository, they would be removed from the shipping containers and placed in double-layered, corrosion-resistant packages for disposal. The design lifetime of the disposal containers is required to be at least 1,000 years, and the current design utilizes an alloy (C-22) estimated to be corrosion resistant for at least 10,000 years. Rail cars would carry the canisters underground into the repository, and remotely controlled equipment would place the canisters on supports in drifts (side tunnels) off of a main underground tunnel. DOE is still exploring whether the plan should include backfilling the tunnels or ventilation should be maintained to keep the packages dry, and whether to keep the repository "hot" or “cold” (i.e., above or below the boiling point of water).

An 8-kilometer-long tunnel called the Exploratory Studies Facility has been bored through the mountain at the depth where a repository would be constructed. Several tests continue at the site to gather data on water flow through the medium, on the behavior of the rock when it is heated (as it would be by the waste), and on other unresolved technical questions.

Under the Nuclear Waste Policy Act, the law governing disposal of spent nuclear fuel and high-level waste, the first HLW repository in the United State will be allowed to accept no more than 70,000 MTHM of spent nuclear fuel and HLW until a second HLW repository is in operation. DOE has allocated space for 63,000 MTHM of commercial spent fuel and for 7,000 MTHM equivalent of DOE HLW and spent fuel. The 70,000 MTHM limit is not a technical capacity limit but a legislated limit.

3
High-Level Radioactive Waste

The majority of HLW is the highly radioactive waste stream from reprocessing of SNF (see Sidebar 3.1 for a discussion of reprocessing methods). Other highly radioactive material, such as reactor compartments from nuclear-powered submarines, also fit in this category in Russia, although the United States considers these to be a different class of waste (See Sidebar 1.1).

3.1 HIGH-LEVEL RADIOACTIVE WASTE IN THE RUSSIAN FEDERATION

The total activity of radioactive wastes accumulated at Minatom enterprises, not accounting for wastes injected deep underground, exceeds 2 x 10^9 Ci (see Tables 3.1 and 3.2).

3.1.1 Production Association "Mayak"

Nowadays, the reactor division of PA "Mayak" operates two 1,000 MWth reactors, Ruslan and Lyudmila, producing radionuclides both for military and civilian purposes. Five uranium graphite reactors were shut down between 1987 and 1991. Production of the weapons-grade plutonium at PA "Mayak" ceased in 1987. The radiochemical plant operation started in 1976 and since then its staff has reprocessed spent fuel from different power reactors, as well as from transport and research reactors. During operation of the RT-1 plant, 2,380 tons of spent fuel have been received from domestic and foreign power plants for reprocessing.

Prior to RT-1, PA "Mayak" operated the first radiochemical plant, known as Plant "B," to process irradiated targets from the first production reactor, reactor "A." Plant "B" operated from December 1948 until the 1960s. In 1959, Plant "BB" was brought on

SIDEBAR 3.1: REPROCESSING

The RT-1 plant extracts plutonium and uranium from SNF using the PUREX process. PUREX is an aqueous process in which the declad and crushed fuel matrix is dissolved in nitric acid yielding a feed to a multi-stage cascade that extracts and strips uranium and plutonium (U and Pu). The solutions contain high concentrations of particulates (graphite, silicon, and others) in suspension, so the solution is clarified with filters and organic flocculants. U and Pu (and, currently, neptunium) are extracted with an organic solvent, tributyl phosphate (TBP) in a saturated hydrocarbon similar to kerosene, which leaves behind essentially all of the other constituents. Nitric acid with a reducing agent strips the Pu from the TBP and contact with dilute nitric acid strips the U back into the aqueous phase. RT-1 repeats this process twice. The PUREX process is very effective at recovering nearly all the U and Pu, leaving insignificant levels (one part in one hundred million) of residual contamination with fission products and minor actinides, but the process generates large amounts of waste and cannot separately recover (fractionate) other constituents for recycling or specialized disposal. Radiolysis and chemical processes degrade the TBP, which must be continuously purified, and this purification process also generates large volumes of waste. Equipment choices, such as centrifugal contactors, can achieve some reductions in volume by promoting faster reaction resulting in less exposure and fewer radiolytic effects, but the clarification and extraction processes still generate large amounts of waste.

As processing of SNF continues in Russia, and particularly if the program is to expand to accept VVER-1000 and RBMK SNF and SNF of international origin, the Russian Federation must examine and pursue ways to improve the radiochemical processes employed to carry this out. Other schemes might improve the characteristics of the process with respect to the environment, proliferation (theft of special nuclear material), safety, and economics. These aspects all must be examined.

Several enhancements and alternatives to PUREX are close to being ready for production-scale deployment. These include UREX, TRUEX, volatilization using AIROX; dry reprocessing technologies using flourination, or electrochemical separation in molten salt; and several others.

UREX is a modification of the front end of the PUREX process that uses the reagent AHA (acetohyroxamic acid) to complex Pu and reduce its valence so that the Pu will remain in the aqueous phase when the uranium is extracted into TBP, as in PUREX. This allows high-purity recovery of the U from SNF, leaving the Pu with the minor actinides and fission products. UREX is attractive in systems that keep Pu and the minor actinides together for proliferation resistance and actinide burning (see, e.g., the integral fast reactor concept with pyroprocessing, or transmutation in general with other partitioning techniques).

The TRUEX process uses a strong chelating agent to extract all the actinides except uranium, neptunium, and plutonium from an immiscible organic solvent, such as TBP. TRUEX can recover americium, curium, and higher actinides from the PUREX HLW stream, although it also extracts several lanthanides, iron, and zirconium at the same time (NRC 1996a).

AIROX is a dry process that removes fission products from SNF by volatilizing them during oxidation and reduction cycles, taking advantage of the fact that when oxidized in O_2, UO_2 SNF forms a less dense matrix of U_3O_8. The volume increase cracks the fuel and heat drives the volatile and semi-volatile fission products from the fuel. U_3O_8 is then reduced to UO_2 by H_2 and the cycle is repeated. Pu is never separated from the U and minor actinides in the SNF, and can be loaded with more fissile material and refabricated into fuel.

Flouride volatility processing is based on the fact that U, Pu, and Np form volatile flourides, but few other elements do. The Midwest Fuel Recovery Plant in Morris, Illinois, in the United States (see Section 1.2) was designed to use both flouride volatility and solvent extraction methods, but the plant never operated because of faulty designs that made the plant infeasible to operate.

Molten salt processes rely on the different thermodynamic and electrochemical properties of different elements when dissolved in ionic molten inorganic salts. The dissolved constituents of the SNF can be separated by volatility or by ionic transport, which can be driven by thermodynamic activity differences in different media or by potentials between electrodes. The chief advantage of molten salt processes is their resistance to radiation damage effects and consequently their effectiveness in processing intensely radioactive fuel that has been discharged from a reactor. (Oxide fuels typically must be reduced to metal before separations in these processes.) This technique has been recently tested in Russia in a semiproduction-scale at a research nuclear reactor, with the regenerated fuel reused for fabrication of fuel elements for fast breeder reactor BOR-60.

Other processes based on solvent extraction (dicarbollide, crown ethers, supercritical fluids, and others), ion exchange and adsorption, membranes, precipitation, and others could improve steps in processing of SNF. (See Appendix D of NRC [1996a] for more details.)

line to process production-reactor targets. A partially completed second line of Plant “BB” was found to be unnecessary for production of weapons materials, and the facilities were adapted to create the radioisotope plant, which processes targets from the isotope-production reactors (Cochran et al. 1995).

TABLE 3.1 Generalized Data on the Amounts of Liquid Radioactive Waste (LRW) Currently Generated, Reprocessed, and Stored at the Minatom RF Enterprises

Name of Enterprise	Total		Including:			
			High-level[b]		Intermediate-level	
	Ci	10^3 m^3	Ci	10^3 m^3	Ci	10^3 m^3
LRW generated in 2001						
Minatom RF[a]	1.06×10^8	3800	6.95×10^7	10.9	3.57×10^7	463
PA "Mayak"	7.05×10^7	1170	6.95×10^7	10.8	1.01×10^6	21.1
LRW reprocessed during 2001						
Minatom RF	4.92×10^7	1630	4.68×10^7	17.1	2.32×10^6	17.5
PA "Mayak"	4.68×10^7	438	4.68×10^7	17.1	7.08×10^4	2.26
LRW accumulated by the end of 2001						
Minatom RF	1.84×10^9	469000	3.51×10^8	30.2	1.49×10^9	11400
PA "Mayak"	4.76×10^8	412000	3.51×10^8	29.2	1.22×10^8	473

[a] Minatom RF includes PA "Mayak," Krasnoyarsk MCC, and the SCC.
[b] No official data are available on liquid high-level waste from Krasnoyarsk MCC and the SCC.
NOTE: Does not include wastes disposed deep underground.

SOURCES: Shatalov (2002), Minatom (2002). Some numbers have been rounded.

TABLE 3.2 Generalized Data on the Amounts of Solid Radioactive Waste (SRW) Currently Generated, Reprocessed, and Stored at the Minatom RF Enterprises

Name of Enterprise	Total		Including:				Spent sealed radioactive sources	
			High-level		Intermediate-level			
	Ci	10^3 tons	Ci	10^3 tons	Ci	10^3 tons	Ci	Number
SRW generated in 2001								
Minatom RF	1.28×10^6	863	1.28×10^6	0.905	2.76×10^3	6.06	1.91×10^5	14100
PA “Mayak”	1.05×10^6	1.75	1.05×10^6	0.529	1.69×10^3	0.072	6.54×10^4	1190
SRW treated in 2001								
Minatom RF	5.16	2.68	N/A	N/A	2.84	1.85	N/A	N/A
SRW accumulated by end of 2001								
Minatom RF	2.29×10^8	57100	2.29×10^8	126	3.03×10^4	815	5.03×10^6	68000
PA “Mayak”	2.24×10^8	309	2.24×10^8	43.8	3.27×10^3	100	4.78×10^6	17900

NOTE: Does not include wastes disposed deep underground.

SOURCES: Shatalov (2002), Minatom (2002). Some numbers have been rounded.

For radiation protection of workers, incoming SNF is kept for five to seven years in cooling pools during decay of the short-lived isotopes. The SNF is then chopped up and dissolved in concentrated nitric acid, from which elements are extracted and separated using organic solvents. The final stage of the process produces highly purified metal oxides and their salts. All processes are executed with remotely controlled equipment. The residual solution is subjected to further treatment for extraction of commercially used isotopes.

In the Russian Federation, the uranium extracted from power-reactor SNF is then mixed with more highly enriched uranium from propulsion-reactor and research-reactor SNF and then sent, in the form of uranyl nitrate, for fabrication of RBMK fuel. Plutonium dioxide is transferred to the storage facility located within the plant territory. Plutonium is supposed to be used in the future for fabrication of fuel for fast-neutron reactors. As a result, a closed nuclear fuel cycle could utilize all of the uranium and plutonium.

HLW in the Environment

The largest outflow of radioactive waste into the environment was during the early operational period of the first radiochemical plant, known as Plant “B” (February 1949). In accordance with the technology adopted at that time, the waste water from Plant “B” was poured directly into the Techa River, at an outflow up to 1,000 Ci per day. The total amount of radioactivity released into the Techa River between 1949 and 1956 was 2.75×10^6 Ci (Mokrov 1996). The river flood plain was polluted over a distance of 100 km.

From 1958 on, the largest amount (more than 1.2×10^8 Ci) of liquid intermediate-level nuclear waste accumulated in Lake Karachai (Reservoir 9). In 1957, a chemical explosion in a liquid high-level waste tank resulted in the release of 2×10^6 Ci over a large area (and about 1.8×10^7 Ci deposited in the immediate vicinity of the tank), which led to the formation of the relatively narrow but long East Urals Radioactive Trail (EURT) with a pollution density of 2 Ci Sr-90 per square kilometer over 1,000 km^2, mostly overlying the EURT (Joint Norwegian-Russian Expert Group for Investigation of Radioactive Contamination in the Northern Areas 1997).

In 1967 wind dispersed 600 Ci of radioactive compounds from Karachai Lake and its banks, resulting in contamination of a 30 km^2 territory at a density of 2 Ci Sr-90/km^2. In order to prevent further aerosol dispersion from the lake surface and shores, the area of the lake was diminished from 51 ha in 1962 to 15 ha in 1993 by filling it with gravel and hollow concrete blocks.

Liquid radioactive waste dumped into Karachai Lake caused contamination of underground water. The total amount of radioactive solutions supplied by the lake to groundwater is about 3.5×10^6 m^3, which includes ~ 7×10^4 Ci Sr-90; 2×10^4 Ci-137 Cs; 6.6×10^5 Ci Ru-106; 1×10^5 Ci ^3H; and a considerable amount of uranium, neptunium, and plutonium. The dynamics of radionuclide dispersion in groundwater is an urgent scientific problem (Drozko et al. 1996).

During the 45-year period of nuclear weapons production, PA "Mayak" accumulated 6×10^8 Ci of liquid HLW. This waste could not be vitrified because of its complex chemical composition.

About 2.2×10^8 Ci of solid HLW was stored in 24 reinforced concrete surface structures and about 3×10^3 Ci of intermediate-level waste and low-level waste in 200 near-surface landfills. More than 3×10^8 m^3 of contaminated water was accumulated in industrial ponds created in the Techa River valley (mainly ponds 10 and 11 with areas of 19 km^2 and 44 km^2, volumes of 7.6×10^7 m^3 and 2.3×10^8 m^3, and 1.1×10^5 Ci and 3.9×10^4 Ci, respectively).

The PA "Mayak" area currently contains ~ 8×10^8 Ci of radioactive waste in various forms, which is clearly a serious environmental hazard, primarily because of the possible outflow of radionuclides into the Techa-Iset'-Tobol-Irtysh-Ob' stream system that drains into the Kara Sea.

3.1.2 Krasnoyarsk Mining and Chemical Combine

Krasnoyarsk Mining and Chemical Combine (MCC) is located underground at the closed administrative area Zheleznogorsk, and occupies 360 km^2 on the right bank of the Yenisey river.[1]

[1]Information on wastes discharged to surface waters at the Krasnoyarsk MCC is available in a paper by Georgievsky (2001).

The enterprise includes a complex of production and supporting facilities the core of which are the reactor production facility and radiochemical plant (Stepanova 1996). There is also a storage facility for heat-generating irradiated-fuel assemblies and a factory for nuclear waste treatment. The reactor facility now includes one closed-circuit uranium graphite reactor. This reactor powers an underground station that provides heating and hot water to Krasnoyarsk-26. The radiochemical plant reprocesses irradiated fuel from the reactor.

The MCC currently stores 6,500 m^3 of high-level, sludge-like, legacy nuclear waste from its weapons-grade plutonium production program. The total activity of this waste is 1.3 x 10^8 Ci. Ninety percent of the waste is in the tank complex of the Radiochemical Plant. Located in a rock massif, the underground storage complex comprises nine stainless-steel-lined tanks, each with a capacity of 3,200 m^3. The remaining ten percent of the waste is in a subsurface storage complex consisting of eight toroidal-shaped storage tanks each with a capacity of 8,500 m^3. Four of these subsurface tanks are stainless steel lined and four are lined by carbon steel with epoxy coating.

High-level liquid wastes are initially somewhat homogeneous. During their storage, however, small amounts of silicic acid precipitates are formed that readily absorb radionuclides and that settle out as sludge in the tanks. A multiyear study has shown that the sludge solids basically consist of metal hydroxides (steel corrosion products and aluminum); polymerized forms of silicic acid; oxides of niobium (V) and manganese; ferrocyanides of nickel and cesium; and residues of ion-exchange resins. The sludge solids also contain significant amounts of uranium and plutonium. The main radioactive constituents of the wastes are isotopes of U, Pu, Np, Th, Zr, Nb, Ce, Cs, and Sr.

Intermediate- and low-level liquid wastes are directed to deep-injection disposal into hydraulically isolated, permeable horizons at the injection site “Severny” located 12 km to the Northeast from the main production zone of the enterprise (Compton et al. 2000; Parker et al. 1999; Parker et al. 2000; Malkovsky et al. 1999). The MCC has disposed of waste at “Severny” since 1967. As of 1995, about 5 million m^3 of LRW with total activity of about 260 x 10^6 Ci (decay corrected to 1995) had been injected into two deep aquifers.

3.1.3 Tomsk Siberian Chemical Combine

The Siberian Chemical Combine (SCC) is located near the town Seversk (Tomsk-7). The SCC was commissioned in 1953. The SCC area is 192 km^2 within an observation zone of 1,560 km^2. Within the observation zone area are the town of Seversk, several settlements, and a part of the city of Tomsk.

At present, SCC is a complex for production of plutonium, uranium, and transuranium elements. It has several production facilities among which are a reactor plant running graphite-moderated reactors (ADE-4,5) designed for production of weapons plutonium and electric power; a gas-centrifuge uranium enrichment plant; a sublimate plant for production of uranium oxide and uranium hexafluoride; a radiochemical plant for reprocessing of irradiated standard blocks[2] for production of uranium and plutonium salts; and chemical-metallurgical facilities for fabrication of nuclear materials. SCC also has facilities for storage of radioactive materials, including materials from nuclear warheads that were recently placed into the specialized buildings (Security Council 1994).

Production of plutonium, uranium, and transuranium elements at the SCC results in generation of considerable amounts of liquid, solid, and gas-aerosol radioactive wastes. SCC has 50 storage facilities of liquid and solid radioactive wastes in its territory, including sites for deep injection of liquid radioactive wastes, which up to now have not impacted the biosphere, but present potential hazards for the environment. The total amount of liquid radwaste disposed of in the deep geological formations is assessed to be 4×10^8 Ci, and the amount in surface storage facilities is approximately 1.25×10^8 Ci.

3.1.4 Dimitrovgrad Scientific Research Institute of Nuclear Reactors

The Scientific Research Institute of Nuclear Reactors (NIIAR) is located 5 km to the west of the town of Dimitrovgrad, Ul'yanovskaya oblast. NIIAR is a large research center with seven operating research and power reactors, where studies are performed on reactor materials science, fuel elements and assemblies, techniques for dry SNF reprocessing, fabrication of pluto-

[2]A "standard block" is a fuel element in aluminum cladding manufactured from natural uranium metal.

nium-uranium mixed-oxide fuels, techniques for producing transuranium elements, and fabrication of ionization sources.

The pilot-industrial site (PIS) for disposal of the non-technological wastes from the research installations is located on the territory of an industrial zone near the purification facilities where pretreatment of liquid wastes is carried out before their deep injection disposal (Rybal'chenko et al. 1994). The PIS has operated since 1966.

The horizons selected to host injected wastes are at depths between 1,440 and 1,550 meters (Horizon III) and between 1,130 and 1,410 meters (Horizon IV), with effective thicknesses of 35 and 80 meters, respectively. Injection horizons are hydraulically isolated above and below by low-permeability layers. The groundwater velocity in the geologic formation is rather difficult to assess, but estimates do not exceed one centimeter per year.

3.1.5 Obninsk Institute of Physics and Power Engineering

The Institute of Physics and Power Engineering (IPPE) is located in the town of Obninsk, Moscow oblast, on the left bank of the Protva River about 100 km southwest of Moscow. In the town, there are several institutions with potential radiation hazard to the environment, among which the IPPE and a branch of the Physico-chemical Institute are the main ones. The main type of impact exerted on the environment by the local institutions are radionuclide gas-aerosol emissions to the atmosphere and radionuclide discharges with the waste waters to the Protva River, as well as radionuclide contamination of the subsurface groundwaters.

Since IPPE began operations, 1,100 m^3 of liquid radioactive wastes with a total activity of 1.63×10^5 Ci, and 2.3×10^4 m^3 of solid radioactive wastes with a total activity 0.14×10^5 Ci have accumulated. The radionuclide inventory includes Cs-137, Cs-134, Mn-54, Co-60, U-235, Pu-239, and others.

3.1.6 Production Association "Sevmashpredpriyatie"

The Production Association "Sevmashpredpriyatie" is located in the town of Severodvinsk, Arkhangelsk oblast, on the shore of the Dvinsk Gulf of the White Sea, 35 km west of the town of Arkhangelsk. The "Sevmashpredpriyatie" production association

carries out construction and repair of nuclear-powered ships. Also located there are the dockyard, “Zvezdochka” with a facility for interim storage of radioactive waste, and a nearby base, where testing and partial dismantling, salvage, and disposition of nuclear-powered submarines are carried out.[3]

3.2 HIGH-LEVEL RADIOACTIVE WASTE IN THE UNITED STATES

> “The highly radioactive waste material resulting from the reprocessing of spent nuclear fuel (SNF), including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and other highly radioactive material that is determined, consistent with existing law, to require permanent isolation" (DOE 2001a).

3.2.1 Defense High-Level Radioactive Waste

Nearly all (over 97 percent by volume) of the HLW in the United States was generated by chemical processing of irradiated targets or fuel from production reactors at two sites (the Hanford Site and SRS) as part of the nuclear weapons material production programs. Relatively small amounts (by volume) were produced in reprocessing of SNF from naval reactors at the INEEL, and in reprocessing of commercial SNF at the Western New York Nuclear Service Center (now called the West Valley Demonstration Project).[4] Much smaller quantities are still being generated in processing of “at risk” SNF at the SRS and Argonne National Laboratory-West. Table 3.3 summarizes the volumes of HLW in tanks and the numbers of canisters of vitrified HLW stored at the sites, as of 1999.

The plants that generated the majority of the HLW used the PUREX process to extract plutonium and uranium from the SNF.[5] In these processes, the fuel is typically chopped up, the fuel clad-

[3]These sites are listed here to identify some of the other sites involved in handling and storage of SNF and HLW in Russia.

[4]The Savannah River Site also processed a very small amount of commercial SNF.

[5]The Hanford Site used other processes before it built the PUREX Plant. Argonne National Laboratory-West has a research-scale electrochemical processing system, but it has processed only a small quantity of fuel.

ding is dissolved in one solution, and the fuel is dissolved in another solution, which is then fed into a series of solvent-extraction stages to separate plutonium and uranium from fission products and other fuel material. Various chemicals are added at different steps to facilitate extraction or precipitation of particular species. The HLW effluent from this process, an acidic liquid containing organic chemicals, fission products, and some actinides (such as neptunium and residual uranium and plutonium) was then sent to storage, sometimes with additional chemical processing.

3.2.2 Radioactive Waste in the Environment

In addition to waste dumped in near-surface burial areas and pumped into tanks, tens of millions of curies of radioactivity have been released into the atmosphere, into surface waters, and into the subsurface in the United States as a result of both routine and accidental discharges related to production of nuclear weapons. This has resulted in exposures of workers and the public and in substantial environmental contamination, especially at the Hanford Site. The magnitudes and extent of these exposures and contamination are much lower than at PA “Mayak,” but the parallels are significant.[6]

At Hanford, the plutonium-production reactors themselves released about 12 million curies of volatile fission products to the atmosphere (Heeb 1994), and releases from reprocessing added to that total, especially during the war years (Napier 1992). Table 3.4 (taken from NRC [2001b]) provides a rough estimate of the inventory of high-level waste produced by chemical processing operations between 1944 and 1988. Even today the current inventory of specific radionuclides and chemicals in the HLW tanks is not well known, although efforts are underway to obtain better estimates.

During the early years of plutonium production at Hanford, HLW tank space was in short supply, so operators ran neutralized liquid HLW through a cascade of tanks, using gravity to separate the solid and liquid fractions. The solid fraction, containing most of the actinide elements and strontium, remained in the tanks. The liquid effluents, which contained tritium, technetium, and traces of

[6]Most of the following discussion of Hanford is taken from NRC (2001b).

TABLE 3.3 Quantities of HLW Stored at Sites in the United States

Site	HLW in Tanks (cubic meters)	Vitrified HLW (canisters)	Total Radioactivity (x 10^6 Ci)	Percent of Total Volume	Percent of Total Radioactivity
Hanford Site	200,000	0	384	58.9	15.8
Savannah River Site	130,000	719*	1,730	38.3	71.0
Idaho National Engineering & Environmental Laboratory	9,360	0	300	2.8	12.3
West Valley Demonstration Project	109**	241**	23.3	< 0.1	1.0
Total	339,000	960	2,430	100	100

* Current number is 1,337 as of October 2002.
** HLW from the tanks at West Valley has been vitrified in 275 canisters. Residual HLW encrusted on the tanks is being characterized and sluiced.

SOURCE: DOE (2001b).

other soluble radionuclides[7] were discharged directly into the subsurface.[8] These constitute the largest discharges to the ground at Hanford, by radioactivity (approximately 5 million curies, in the second row of Table 3.4). Groundwater under more than 100 square miles (260 square kilometers) of the Hanford Site is contaminated above drinking-water standards with radionuclides and chemicals, including tritium, strontium-90, technetium-99, iodine-129, uranium, carbon tetrachloride, and chromium. Uranium and toxic chemicals also were discharged to the ground through drains in conjunction with plutonium recovery processes, and at least 67 of the 177 underground tanks at Hanford are known or suspected to have leaked HLW directly into the subsurface. Many of these tanks have exceeded their design lives. The total radionuclide input to the subsurface at Hanford from HLW operations is unknown but is probably on the order of a few million curies (NRC 2001b) (see Table 3.4).

Some of the contaminants released or pumped into the ground have formed large underground plumes that are intersecting the Columbia River, but there were also direct discharges to the river. The largest sources of direct releases to the river were the eight "single-pass" production reactors. These reactors used treated river water as coolant and the neutron-activated constituents, carrying small amounts of fission products, were discharged back into the river. Heeb and Bates (1994) estimate that about 110 million curies were discharged to the river, although most of this was short-lived (half-lives on the order of days or less) and would not be considered HLW.

Although SRS and INEEL have zones of contamination from a variety of sources, including buried wastes, little of this contamination is the direct result of leaks or releases of HLW. There has been some HLW leakage into the subsurface at the Idaho site from valves and a severed waste transfer line; the amount of leakage is on the order of a few tens of thousands of curies. At Savannah River a small amount of HLW (on the order of tens of liters) is known to have leaked into the subsurface from one tank, and several tanks have had leaks from their primary shell into the annular region between the shells.

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[7]Cesium was in the liquid waste stream during operation of the cascade of tanks until the 1950s. After that, cesium was precipitated in some tanks with ferrocyanide and the remaining supernate was still dumped in the ground.

[8]HLW volumes at Hanford were reduced by about a factor of 10 by this chemical treatment/discharge process and evaporation.

TABLE 3.4 Inventory of High-Level Waste in the 200 Area at the Hanford Site

	Waste Volumes (millions of gallons)	Curies to Ground (millions)[a]	Curies in Facilities (millions)[a]	References
HLW Generated	530	—	—	Agnew (1997)
Direct Discharges to Soil[b]	120-130	0.065-4.7[c]	—	Waite (1991); Agnew (1997)
Tank Leaks to Soil[d]	0.75-1.5	0.45-1.8	—	Waite (1991); ERDA (1975); Agnew (1997)
Evaporator Condensates Discharged to Soil	280	0.003	—	Agnew (1997); Hanlon (2000); Wodrich (1991)
Cooling and Processing Water	400,000	Negligible	—	DOE (1992b,c)
Cs and Sr Capsules	—	—	140	DOE (1996b) Appendix A, Table A.2.2.1
Tank Waste	54		210-220	Waite (1991); Agnew (1997); Hanlon (2000)
Facilities	—	—	10[e]	Gephart (1999)
Totals		0.22-6.5	360-370	

NOTE: Numbers are rounded to two significant digits from the values given in the references. The numerical ranges represent differences in estimating procedures and do not necessarily represent uncertainty ranges of the estimates themselves, which have not been determined, in part because the quality of the estimates are unknown.

[a]Quantities are decay corrected to the mid-to-late 1990s.

[b]After cascading through multiple tanks or after chemical treatment to remove cesium.

[c]The lower estimate is for Cs-137 and minor amounts of Sr-90 only.

[d]Estimate does not include leaks from transfer lines and valves.

[e]Radionuclides estimated to remain in plutonium production reactors and chemical separations facilities.

SOURCE: NRC (2001b).

3.2.3 High-Level Radioactive Waste from Processing Commercial Spent Fuel

Two commercial reprocessing plants were built in the United States: the Nuclear Fuel Services facility near West Valley, New York, with a 300 MTHM per year design capacity, and the Midwest Fuel Recovery Plant in Morris, Illinois, also with a 300 MTHM per year design capacity. A third facility, the Allied General Nuclear Services plant in Barnwell, South Carolina, designed to process up to 1500 MT per year, was never completed. The Midwest Fuel Recovery Plant was completed but was found to profound design flaws in 1974, and was not put into operation, but is used as a storage site for SNF.

The Nuclear Fuel Services plant (also called the Western New York Nuclear Service Center and later the West Valley Demonstration Project) primarily used the PUREX process, but also used the THOREX process for some thorium-bearing fuels, and began operating in 1966. The plant processed approximately 640 MTHM, roughly 60 percent of which was from the N-Reactor at Hanford, and the remainder was from commercial nuclear power plants. The facility shut down in 1972 to make modifications intended to seismically stabilize the facility and increase its capacity, but it never restarted. In addition to the fuel reprocessed at West Valley, a very small amount of commercial SNF, 0.7 MTHM, was reprocessed at SRS (EIA 1999a).

During operations, the West Valley facility generated approximately 2,000 m^3 of liquid high-level waste that was stored in two underground tanks: a 51- m^3 stainless steel tank, and a 2,800-m^3 tank made of carbon steel. Another identical set of tanks was left empty during operations, but has been used in treating the tank wastes. The program to vitrify liquid HLW at West Valley was completed in August 2002 with the production of the last of 275 vitrified logs.

3.3 END POINTS FOR HIGH-LEVEL RADIOACTIVE WASTE THAT IS NOT SPENT NUCLEAR FUEL[9]

At the PA “Mayak” plant, the liquid HLW is vitrified in the EP-500 electric ceramic melter. The phosphate glass fabricated in this melter is poured into containers and then moved to the temporary storage facility in the RT-1 plant vitrification area. The first

[9]End points for SNF are addressed in Section 2.4.

EP-500 melter lasted one year (there were problems with the current supply and coolant). The second melter was in continuous operation for six years (1995-2001). Over the course of this operation as much as 12,000 m^3 of the high-level liquid waste were reprocessed to produce more than 2,300 tons of glass (total radioactivity of approximately 3 x 10^8 Ci), which are currently stored. The third EP-500 melter was put into operation in 2002.

To end the practice of dumping liquid intermediate-level waste into open waters at PA "Mayak" (Lake Karachai and the Techa Ponds Cascade), PA "Mayak" is developing a technology for joint vitrification of high-level and intermediate-level waste in the EP-500 melters.

Work has been done to develop an induction melter, with a "cold" crucible provided with an inlet direct-feed evaporator, to allow reprocessing of liquid waste of a wide range of compositions to produce materials with desirable properties (glass and mineral-like crystal matrices). By using different mineral-like matrices, stabilized compounds can be produced for a variety of waste forms. PA "Mayak," however, currently has no plans to switch to a cold crucible melter and has a fourth melter of the current design already installed for use when the new third melter reaches its end of life. Thus, the newer technology is not yet in use.

Metal radioactive waste (parts of irradiated fuel assemblies, fuel cladding, etc.) are sent for storage in specialized storage facilities. A technology for induction-slag remelting of such waste in the "cold" crucible has been developed to reduce the volume of metal radioactive waste by 5-6 times and to decontaminate the metal, thereby decreasing the residual activity by two or three orders of magnitude, raising the possibility of reuse.

Fiberglass and gauze filters and adsorbers are used in the gas cleaning systems of the plant and the nuclear power plant to remove aerosols and iodine from gaseous releases.

3.3.1 Nuclear Waste Underground Disposal and Disposition in the Russian Federation

Geological disposal of solid and solidified HLW is considered in Russia as being economically, technically, and ecologically the most attractive approach to completion of the nuclear fuel cycle. In accordance with previous decisions by Minatom, work on selection of the sites for HLW disposal and construction of SNF

storage facilities are assigned and planned at the radiochemical enterprises: PA "Mayak," Krasnoyarsk MCC, as well as in the regions of the nuclear Navy bases in the Russian Far East and Northwest. The first stage of developing repositories is construction of underground research laboratories at sites at the PA "Mayak," at the Krasnoyarsk MCC, and in the Northwest region.

Production Association "Mayak"

At present, more than 2,000 metric tons of radioactive aluminophosphate glass from vitrification of liquid HLW with total activity about 3 x 10^8 Ci is stored at PA "Mayak." In addition, liquid HLW with a total activity of about 3.77 x 10^8 Ci, which also is destined for vitrification, is currently stored in the special-purpose reservoirs. All vitrified HLW at PA "Mayak" is destined for underground disposal within the area of the enterprise's sanitary-protection zone (SPZ).

The SPZ territory is formed by volcanic rocks of andesite-basalt composition, which have effective physical and geochemical isolation capabilities.[10] The rock massif is, however, cross-cut by numerous irregularly distributed faults of different scales. Within the fault zones, rocks are strongly tectonically disturbed and are characterized by increased permeability. Within the inter-fault zones, relatively weakly disturbed areas have been found, from which two sites were selected for their promise as possible repository locations. After detailed studies, a site for construction of the underground research laboratory is to be chosen with the prospect of its subsequent conversion to the underground repository.

Krasnoyarsk Region

A team of experts representing Ministry of Atomic Energy institutions, the Russian Academy of Sciences, and other organizations has examined where to locate a HLW repository in the region of the Krasnoyarsk MCC. Such a repository would be de-

[10]Volcanic rocks at the PA "Mayak" region were subjected to metamorphic overprint that resulted in reduction of their permeability. The average sample permeability of the host rocks section is ~10^{-19} m^2, porosity is 0.4% (Petrov et al. 1998). The data on transport properties of the Far East region basalt seria are not yet available and will require study.

signed to accept solidified HLW and SNF from the Krasnoyarsk MCC, including wastes from RT-2 if it is completed and operated.

The examination was carried out by using a stepwise approach: from the stage of searching for promising geological formations to the stage of choosing promising sites. Based on the results obtained from research to date, and taking into account socio-economic and environmental factors, the Nizhekansky granitoid pluton was selected as a candidate rock massif. The potential host rocks are biotite granites and granodiorites. The studies of the massif helped to identify several promising sites with low rock permeability and high tectonic stability. Geological and geophysical work provided a basis for selecting the two most promising sites: the “Itatskiy” and the “Kamennnyi” sites, each with an area of 7 km^2, and both located about 25 km to the southeast of the Krasnoyarsk MCC. At present, investigations for choosing the most promising site for designing an underground research laboratory are being conducted.

Northwest Region

An international team of experts, operating under the collaborative Russian-European Tacis project, completed a study in 2001 of issues related to interim storage of SNF and disposal of radioactive waste from operating and decommissioned nuclear-powered submarines in the northwest region of Russia, as well as from the Kola Nuclear Power Plant. The study included selection of storage and disposal sites, facilities arrangement, and technical equipment.

Expert participants in implementation of this project were from the Russian Academy of Sciences, Minatom RF, scientific-research institutions of the Arkhangelsk oblast, as well as experts from Belgium and France. At the first stage of the project implementation, 25 candidate sites were selected within the region. From these, after analysis, 7 sites were recommended for more detailed assessment. After additional studies, at the closing stage of the project, two sites were selected as potentially favorable for SNF long-term, dry, on-surface storage and for geologic disposal of radioactive waste. One site is located near the Navy bases and enterprises for dismantling, salvage, and disposition of nuclear-powered ships at the northern, low-seismicity coastal zone of the Kola Peninsula. The second site is at the southern, low-seismicity coastal zone of the Kola Peninsula. Both sites are formed by old

crystalline rocks dominated by granitoids, granite-gneisses and migmatites characterized by high strength, low permeability, and insignificant tectonic disturbance.

At present, financing is needed for engineering studies at the selected sites, for development of the on-surface infrastructure, and for preparation of mining works for construction, equipment, and operation of an underground research laboratory with the prospect of its subsequent conversion to an underground repository.

Far East Region

In the Far East region in the southern part of the Primosky Krai, the Artemovsky site, located at a distance of 70-80 km to the northeast of Vladivostok city, may be recommended for the underground interim dry storage of SNF and other radioactive materials from nuclear-powered submarine (NPS) operation and decommissioning.

The territory of the region is formed by terrigenous-sedimentary coal-bearing clayey-sandstone neogenic rocks covered by the mantle of tholeiitic plateau basalts and neck facies of alkaline basalts. The total thickness of volcanic formations reaches 300 meters, and their absolute age is about 4 million years. Plateau basalts and alkaline basalts have appropriate physical and geochemical isolation properties and may be utilized as a host media for construction of a facility for SNF underground dry storage.

The sharply rugged topography of the Artemovsky site with the altitudes varying from 600-700 m up to 1,200-1,250 m suggests that horizontal drifts, which can be used as access and emplacement tunnels, would be the most reasonable construction option for a storage facility. Such construction has significant technical and economical advantages in comparison with a shaft-fed facility, as it eliminates the need for the shaft well with the lowering and lifting equipment, and simplifies and reduces the cost of the water pumping and ventilation.

The relative proximity of the Artemovsky site to the city of Vladivostok—a large administrative and industrial center—and the presence of a developed transportation network in the territory make it a potentially desirable host area for construction of the underground storage facility.

Transbaikal Region

The Priargunsky Industrial Mining Chemical Association (PIMCA), located in the southeastern Transbaikal egion (Chitinskaya oblast, town of Krasnokamensk), is under Minatom administration. PIMCA is the only enterprise in Russia carrying out mining and processing of uranium ores, and it is in a region that is a promising site for an underground interim dry storage facility for SNF and other radioactive materials. The region is located at a significant distance from large settlements and industrial centers, but is connected to other regions of Russia by a railway line and automobile roads.

The region under consideration is a low-seismicity zone. Most of its territory is formed by massive crystalline rocks with high mechanical stability, low permeability, effective isolation properties, and weak tectonic disturbance. Like the Artemovsky site, the rugged topography, with altitudes varying from 600 m up to 900-1,000 m, allows horizontal access and emplacement tunnels.

Collection of additional materials at the selected sites is needed for a clearer understanding of the geological, hydrogeological, geophysical, and other conditions for development of underground SNF and HLW storage and HLW disposal facilities (Velichkin et al 2002).

3.3.2 Nuclear Waste Underground Disposition and Disposal in the United States

At the Hanford site, the SRS, and the West Valley Demonstration Project, the acidic liquid effluent was neutralized with sodium hydroxide for storage in carbon-steel tanks. This neutralization process produced a metal-rich precipitate known as sludge. To conserve tank space, the HLW at Hanford and Savannah River was concentrated using evaporators to drive off excess liquids. This produced a salt-rich slurry that if sufficiently concentrated, crystallized into a solid salt cake upon cooling. As a result, the HLW in storage at Hanford and Savannah River exists in several physical forms: liquid, salt cake usually containing interstitial liquid, slurries (liquids with suspended particles), and sludge. Over 98 percent of the roughly 3.5×10^5 m^3 of tank wastes are aqueous liquids or slurries (DOE 2001b). Current efforts to immobilize HLW at SRS and Hanford for disposal are greatly complicated by the waste's physical and chemical heterogeneity.

The HLW stored in the tanks at Hanford is especially complex as a consequence of its history of production and management. Prior to about 1952, reprocessing at Hanford was carried out using a bismuth phosphate process, which produced dilute wastes that contained high concentrations of uranium. After the REDOX and PUREX processes were introduced starting in the early 1950s, the HLW was more concentrated and, in some cases, became self-boiling after being pumped into the underground tanks (in fact, heat loads were sufficient to damage some of the tanks). To reduce heat loads, cesium and strontium were removed from the HLW by chemical precipitation and ion exchange processes. The separated strontium and cesium were loaded, in the form of halide salts, into steel capsules used as irradiation sources onsite and offsite. These high-intensity sources are currently stored at Hanford. These materials will presumably be disposed in a geologic repository, but the exact disposition pathway is unclear at present.

Experience in the United States has shown that storing liquid HLW in underground tanks for decades past their design life is unreliable and hazardous. Physical and chemical processes in the waste result in waste forms that are difficult to manage. Leaks from degraded storage tanks have resulted in plumes of contamination that are hazardous and difficult to clean up.

The liquid HLW at INEEL was handled and processed differently from the waste at Hanford and SRS. After production, HLW was temporarily stored in stainless steel tanks and then processed in a fluidized-bed chemical reactor to produce a granular ceramic, referred to as calcine. This calcine HLW is stored in stainless steel bin sets within concrete vaults that are designed to last for 500 years.

HLW is to be disposed of by DOE in a deep geologic repository after it has been put in a form suitable for disposal. Immobilization in borosilicate glass (vitrification) is the waste form that has already been selected for HLW at SRS and the West Valley Demonstration Project. Each of these sites has its own vitrification facility.

The Defense Waste Processing Facility (DWPF) at SRS, which uses a joule-heated melter, is the largest HLW-vitrification facility in the world. The facility began vitrifying radioactive waste in 1996 and expects to vitrify all of the HLW currently stored at the SRS in 20 to 25 years, producing the molten-glass waste form into approximately 6,000 stainless steel canisters. As of May 2002,

almost 1,300 canisters of HLW glass have been made and are stored in an underground storage vault in the Glass Waste Storage Building (WSRC 2001).

The West Valley Demonstration Project started to vitrify its liquid high-level radioactive wastes in 1996 and completed its efforts in 2002. The West Valley facility used a joule-heating melter to produce borosilicate glass to immobilize the waste from that reprocessing plant. As of August 2002, 275 canisters of vitrified HLW had been made and stored in racks in the High-Level Waste Interim Storage Facility.

Vitrification is being examined for HLW at the two other major sites: the Hanford Site and INEEL. Other technologies for immobilization are also under consideration.

A program has been struggling for several years to develop a vitrification facility at Hanford, called the Waste Processing and Immobilization Facility, to retrieve and immobilize some of the high-level wastes in the 28 double-shell tanks. This will include most of the liquid from the 149 single-shell tanks, which is being pumped into the double-shell tanks. Plans for the solid and semisolid wastes remaining in the single-shell tanks are still being developed. Construction of the vitrification facility began in 2002, and vitrification of radioactive material is to begin in 2007. Immobilizing the waste is expected to take about 30 years. Waste will be stored onsite prior to shipment for disposal at a mined geologic repository. Some residual contamination will remain in the tanks and substantial quantities of low-activity waste will be generated in the pretreatment and immobilization process. DOE does not consider these residual and low-activity wastes to be HLW and is seeking alternatives for managing these wastes.

Plans are still being developed for the calcine HLW and salt-bearing wastes at Idaho. The calcine HLW will be converted to another form and, following treatment, it is expected to be sent to a geologic repository for disposal.

4
Conclusions and Recommendations

The current state of affairs regarding end-point issues in Russia and the United States is that the practical activities of managing spent nuclear fuel (SNF) and high-level radioactive waste (HLW) in the two countries now are similar in many respects. In the United States, the majority of SNF is in storage and is likely to remain so for at least two decades. In Russia, only a limited portion of the commercial SNF (from VVER-440 reactors) undergoes chemical reprocessing, while most of the commercial SNF (from RBMK and VVER-1000 reactors) at present is being stored. At the same time, both countries chemically process liquid HLW in order to immobilize it for safer storage and disposal.

The United States and Russia, however, have different approaches to and long-term strategies for realization of end points for SNF and HLW. The United States currently plans to transport SNF to a geologic repository for disposal without chemical processing. Russia plans to develop the capacity to chemically process all of its SNF to recover and reuse uranium and plutonium in reactors, while immobilizing the HLW from the processing, and disposing of the immobilized waste in geologic repositories at the processing sites. Each approach has its advantages and disadvantages. Selection of end points and approaches to end points can be informed by science and engineering, but the selection involves policy decisions that incorporate economics, political considerations, and in some cases, international relations. Such decisions must address both interim, short-term end points and final long-term end points. In doing so, safety, environmental impact, and proliferation concerns must be included.

Geologic disposal has been considered the most promising option for disposition of high-level radioactive waste since at least 1957, when a report of the National Research Council (1) concluded that “wastes may be disposed of safely at many sites,” (2)

suggested that "disposal in cavities mined in salt beds and salt domes" promises "the most practical immediate solution of the problem," and (3) noted that solidifying the waste into an insoluble form would simplify disposal (NRC 1957). That early report noted that a great deal of research was still needed. Indeed, institutions charged with planning and carrying out geologic disposal have encountered major political and technical difficulties. Most communities are not receptive to hosting a HLW repository,[1] and some groups oppose disposal because of concerns about environmental damage and as a way to strike at nuclear power.

Most of the technical challenges are related in some way to uncertainty. Understanding the mechanisms and characterizing the features of environmental systems is a much more difficult task than it was thought to be 45 years ago. Understanding the disposal environment and how it interacts with the engineered facilities and packages placed in it provide the basis for predicting behavior. Scientists must make predictions spanning, in some cases, tens of thousands of years to respond to regulatory guidance and requirements. Such predictions necessarily involve uncertainties, even when the physical, chemical, and biological phenomena involved are well understood. The time and effort expended in countries that have geologic disposal programs attest to the difficulties, and scientific understanding of the phenomena involved is still evolving.

A recent report by an international committee of the National Research Council nonetheless concludes that geologic disposition is the only long-term end point that does not require continued management and resource expenditures (NRC 2001a). Worldwide, no engineered geologic repository for HLW has been designed and operated as yet, although the Waste Isolation Pilot Plant (WIPP) in the United States is an operating geologic repository for long-lived transuranic waste. The WIPP is approximately 700 meters underground, mined out of bedded salt.

The committee draws from previous studies by the National Academies in recommending a risk-based approach to management and disposition of HLW and SNF and cleanup of contaminated sites. These studies were not specific to the United States—

[1]There are communities that have been receptive, but they are few and nearly all are situated within larger regions that are opposed to hosting a repository.

most were explicitly generic regarding the national context—but most were applied to specific cases in the United States. By a "risk-based approach," the committee means that the U.S. Department of Energy (DOE) and the Ministry of Atomic Energy of the Russian Federation (Minatom) should prioritize their efforts based first on the risks posed by the problem, situation, or condition. The first step in setting such priorities is to characterize and understand the risks. Risk analysis and characterization, and indeed the overall decision-making process, are societal processes that need participation from the public to function properly. "Adequate risk analysis and characterization ... depend on incorporating the perspectives and knowledge of the interested and affected parties from the earliest phases of the effort to understand the risks. The process must have an appropriately diverse participation or representation of the spectrum of interested and affected parties, of decision makers, and of specialists in risk analysis, at each step" (NRC 1996b, p.3).

Risks in some cases are substantial and more or less immediate (such as the buildup of flammable gas mixtures in the tanks at Hanford in the 1980s and 1990s), so their priority is clear even before the risks are well characterized. But once measures are taken to mitigate immediate risks, a more thorough understanding is needed for the next step, which is to assign priorities among the less critical problems.

The second element of a risk-based approach is seeking effective technical solutions for problems. Where effective solutions are not at hand, risks must be managed while a program of research and development (R&D) for effective solutions is pursued. Effective solutions are best developed when a set of desired end points or end states (a reference end state and alternatives) have been identified (see Sidebar 4.1). The R&D programs are more likely to succeed if they pursue multiple technological alternatives to address each problem until a clear winner is apparent (NRC 1999c). This approach would enable DOE to pursue a phased decision strategy rather than a phased implementation strategy for the one alternative (NRC 1996c).

This approach applies not only to managing liquid HLW in corroding tanks and remediating contaminated ground water, but also to disposition of radioactive waste in geologic repositories. Reports by the National Research Council (1990, 2001a, 2002b) recommend that those who run HLW-repository programs develop

SIDEBAR 4.1: An End State Methodology

A National Research Council (NRC) report specifically addresses the question of how to identify technology needs for DOE's environmental and waste management problems. The NRC report (1999c) recommends a systems engineering approach that entails "structuring of remediation scenarios (i.e., a reference scenario and several alternatives) to identify the technologies required to reliably achieve the goals of radioactive waste management in the face of uncertainties about the future."

The report lays out the end-state approach in seven steps.

1. Characterize the initial state or condition of the wastes and site to be remediated.

2. Identify reference and alternative scenarios to accomplish the general remediation objective.

3. Specify the waste forms and environmental conditions as the desired end states.

4. Define the functional flowsheets required to transform the initial waste or waste site into the desired end states.

5. Combine essentially identical functions in the flowsheets into a unique set of functions.

6. Allocate end-state specifications to each processing function as functional requirements.

7. Assess the respective development or deployment status of the technology required for each function to yield technology needs.

a stepwise approach to implementation. The development of a safety case[2] as part of a stepwise approach facilitates continuous learning and can help address the technical and societal uncertainties associated with HLW repositories. Geologic repositories that are intended to isolate wastes from the biosphere for anywhere from centuries to hundreds of centuries are an unprece-

[2]A safety case is defined as " … a collection of arguments, at a given stage of repository development, in support of the long-term safety of the repository. A safety case comprises the findings of a safety assessment and a statement of confidence in these findings. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages" (NEA 1999b).

dented engineering endeavor. “[A] stepwise process that allows for continuing improvement of scientific understanding is appropriate for decision making” (NRC 2001a, p. 21). “For both technical and societal reasons, national (HLW repository) programs should proceed in a phased or stepwise manner, supported by dialogue and analysis” (NRC 2001a, p. 42).

In both countries progress is being made in handling the radioactive waste problems. In Russia, progress is being made as HLW at PA “Mayak” is immobilized in aluminophosphate glass logs and stored onsite; interim storage facilities are planned for SNF at several sites; efforts are underway at the Krasnoyarsk MCC to extend the capacity of the wet storage facility and to design and plan construction of a dry storage facility for VVER-1000 and RBMK SNF; and the rate of defueling of decommissioned nuclear-powered ships has increased. In the United States, DOE and other managers of SNF have made progress in achieving interim end points for SNF and HLW: nearly all SNF in the United States is in safe storage in cooling pools or in dry casks; HLW at West Valley has been vitrified and HLW at the Savannah River Site (SRS) is in the process of being vitrified and stored; calcined HLW at the Idaho National Engineering and Environmental Laboratory (INEEL) sits in stainless steel bins that are deemed to be safe for centuries; and TRU waste has begun to be shipped to the WIPP facility, which opened in 1999. Overall progress, however, has been slow and much more work remains to be done in both countries.

4.1 PROBLEMS THAT REQUIRE IMMEDIATE ATTENTION AND PROMPT ACTION

As is described in the previous chapters of this report, Russia and the United States face many similar problems, but Russia is at a different stage from that in the United States in addressing its problems (see Bradley et al. 1996). The creation of the Office of Environmental Management within DOE in 1989 signaled the increased attention, efforts, and funding the United States began to devote to environmental and waste-management problems in its nuclear-weapons complex. The annual funding for this office is now approximately $7 billion. DOE has addressed problems that pose immediate risks to workers and the public, although many of the problems still require attention, because the measures taken have been temporary solutions.

Russia has made efforts to address the most serious environmental and waste-management problems within its nuclear complex, and has made progress on some of them. But the resources available for these activities in Russia have been much smaller, and some of the problems, particularly the environmental contamination, are more difficult and urgent than their counterparts in the United States.[3] As a result, the timeframe for dealing with the problems requiring near-term actions in Russia is different from that in the United States. Therefore, the problems highlighted in this section concerning Russia require action with timeframes of months or years, and those concerning the United States require action over the next several years. The committee would like to emphasize that each nation's problems are important and demand attention, but Russia's problems need more immediate action to protect the security, safety, and health of people and the environment.

4.1.1 Immediate Problems in Russia

In Russia these problems include several that the committee has identified to be of greatest concern. The order of the first two has been debated, but all committee members agree these are the first two concerns.

The potential for terrorist attacks involving liquid HLW stored in tanks at radiochemical enterprises.

HLW and SNF present both potential targets for terrorist attacks and potential material for manufacturing radiological weapons (including so-called "dirty bombs"). These wastes are located at many sites and, in some cases, are not sufficiently protected. The physical form of SNF makes it more difficult to dis-

[3]Consider, for example, the liquid wastes at PA "Mayak" stored in the Techa Ponds Cascade, held in place by earthen dams whose failure would threaten substantial contamination of the river. As a crude parallel, consider the leaking single-shell tanks at Hanford, which leak into a relatively thick unsaturated subsurface, tens of kilometers from the Columbia River, and from which essentially all of the liquids have been removed to sturdier double-shell tanks. The waste must be dealt with in both cases, but the problem in Russia is more immediate compared with the problem in the United States.

perse its radioactive constituents than those of liquid HLW. Nonetheless, all SNF should be provided immediately with proper physical protection, and sites storing intense radiation sources should be placed under constant monitoring. To reduce the potential for terrorist attacks and vulnerabilities associated with stored liquid HLW, governments should deploy physical protection systems capable of preventing successful attacks and should accelerate programs to immobilize that waste.

The potential theft of HEU and plutonium

Because of the potentially horrible consequences of the theft of nuclear materials containing highly enriched uranium (HEU) and plutonium, efforts to prevent such thefts should be strengthened. This can be accomplished by improving materials protection, control, and accounting (MPC&A) at sites where HEU (including HEU SNF from research and propulsion reactors) and plutonium are stored and by consolidation of these materials in well-protected, centralized facilities, such as PA “Mayak.” Accelerating completion of the specialized plutonium storage facility at PA “Mayak” would facilitate these efforts.

Northern Fleet SNF

Many of the spent fuel assemblies in storage, and the storage facilities themselves, are in poor condition and constitute serious hazards. The largest SNF storage facility in the region, Andreeva Bay, has a “short-term” facility that has been in operation for over 18 years and does not meet current safety requirements. Some of the assemblies sit in containers in an open area. These storage facilities should be upgraded or new ones should be built, and efforts should proceed toward developing a new underground geologic repository in the region.

Decommissioned nuclear-powered submarines awaiting unloading of SNF

Dozens of decommissioned nuclear submarines await defueling. As soon as possible, plans should be implemented for this fuel to be unloaded and shipped for safe storage at PA "Mayak" or properly stored at specialized facilities on shore.

Dumping of liquid radioactive wastes at PA "Mayak" into Lake Karachai and the Techa Ponds Cascade

Liquid radioactive wastes continue to be dumped into Lake Karachai and the Techa Ponds Cascade at the PA "Mayak." This leads to serious risks of further environmental pollution, including underground and surface-water contamination. Moreover, there is a threat of dam failure, which could result in contamination of the Techa water basin with water bearing radioactive waste. In order to reduce on-going contamination and to prevent accidents, the practice of dumping of liquid radioactive wastes into Lake Karachai should be discontinued in the future and appropriate actions should be taken to decrease the water level in the Techa ponds cascade.

4.1.2 Near-Term Problems in the United States

Several problems in the United States require action over the next several years.

Prevent Use of Nuclear Materials for Terrorist Acts

While Russia has been aware of terrorist threats, the events of September 11, 2001, made the United States focus on the necessity to address potential terrorist acts, and this has led to many reviews of vulnerabilities of nuclear power stations and all facilities where radioactive materials are stored and used (see, e.g., NRC [2002]). These reviews have not been completed, but should be completed as quickly as feasible, and near-term actions should be taken to address the vulnerabilities identified in these reviews.

Hard-to-retrieve HLW in corroded or damaged single-shell tanks at Hanford

Some forms of HLW in underground tanks are difficult to retrieve and, particularly in the case of single-shell tanks at Hanford, pose substantial risks of further environmental contamination. It is not clear that existing technical solutions are adequate or acceptable for addressing this problem, which may delay ac-

tion. These issues probably will require research and development.

Corroding N-Reactor fuel at Hanford

Some SNF from the N-Reactor at Hanford is in very poor condition and is stored in cooling pools (the “K-basins”), one of which has leaked. Efforts to stabilize, dry, and package this fuel should be expedited and a disposition path should be found for the corrosion products and sludge from this fuel.

A disposition program for excess weapons plutonium that has an ambitious schedule and has not taken crucial steps

As noted in Chapter 2, current DOE plans are to complete designs for the MOX fuel-fabrication facility in 2003, complete the licensing in 2005, to begin hot startup of the facility in 2007, and to load the first MOX fuel into a reactor in August 2008. This is an ambitious schedule, particularly since there is not a decision yet on how to manufacture the lead test assemblies so that they can be tested (and licensed) for use in a commercial reactor, and because one of the two utilities that had originally signed up for the MOX program has pulled out. DOE should settle on a final plan for manufacturing the lead test assemblies, and establish a schedule that will lead to putting weapons plutonium, in MOX-fuel form, in a U.S. commercial nuclear power reactor no later than 2010.

4.2 LONGER-TERM RESEARCH, DEVELOPMENT, AND IMPLEMENTATION

Several problems in Russia and the United States demand attention in the form of research, development, and implementation. In addition to the areas of work described in this section, most if not all of the problems described in Section 4.1 will also require research, development, and implementation with a longer-range view than is implied by the call for urgent action in Section 4.1. Those problems are not reiterated in this section.

4.2.1 Nuclear Fuel Cycles

The desirability of a nuclear fuel cycle (open or closed) depends on many factors, some of which are technical but many of which have social, economic, and political dimensions, and each of these might be different in different countries or at different times. It would be worthwhile to conduct a systematic comparison of nuclear fuel cycles in Russia and the United States to understand better the factors and conditions that might encourage or discourage each approach in the future.

Further, Russia plans to increase the role of fast reactors in its nuclear fuel cycle and so will need to choose between different options. To this end, Russia should carry out a comparative analysis of the efficiency of two approaches to organization of the closed nuclear fuel cycle with fast reactors: (1) using fast neutron reactors with conversion ratios of approximately 1.05 to 1.1, which require plutonium generated in thermal reactors for their primary feed, and (2) using fast reactors with more efficient breeding (conversion ratio of approximately 1.6), which make an independent fuel cycle possible without preliminary plutonium production in thermal reactors. Comparison of the results obtained will help Russia to select what approach is preferable or to take a decision on collateral implementation of both options.

4.2.2 New Work on Reprocessing

Russia plans to reprocess VVER-1000 SNF at the future RT-2 plant at the Krasnoyarsk Mining and Chemical Combine. If this is to be realized using new technologies, then a special line for reprocessing of this SNF must be designed for RT-2 or, if construction of RT-2 is canceled, then this line can be deployed at the operating RT-1 plant at PA “Mayak.” The economic aspects do not warrant expedited reprocessing of this SNF, so Russia plans to store VVER-1000 SNF until economic incentives arise.

RBMK fuel is currently less attractive for reprocessing than other SNF, in part because of the low enriched uranium it uses, and in part because the isotopic composition of its plutonium is not particularly suitable for MOX fuel for thermal reactors. Development of an economically acceptable technology for reprocessing of RBMK SNF would help Russia to realize its goal of a closed fuel cycle.

The PUREX process, which has been used for nearly all processing of SNF in both the defense and commercial nuclear programs, generates large amounts of waste that must be further processed before it can be immobilized for disposal. In addition, current closed nuclear fuel cycles are more expensive than the open fuel cycle, and it is doubtful that closed fuel cycles will be economically competitive if they use PUREX technology. In Russia, alternative processes and improvements to the PUREX process should be carefully considered. For example, should different fuels with different isotopic compositions be treated separately or with different processes, particularly if the objectives are different? A Russian research and development program, drawing on and coordinating with international efforts in these areas, could dramatically reduce the risks and impacts of an expanded SNF processing program in Russia, and might improve the economic features of the program.

Such studies of non-PUREX processes may become important also for the United States as the government pursues the recommendations of the national energy policy announced by the administration in 2001 (National Energy Policy Development Group 2001). In any case, both nations would benefit from examining current processing flowsheets for both HLW and SNF and revising them as necessary to ensure that there will be significant improvements in the forms, and net decreases in the amounts, of radioactive waste that are generated. All analyses of reprocessing options should include consideration of proliferation risks.

4.2.3 Further Develop MOX-Fuel Fabrication Technology

As noted above, Russia plans to use MOX fuel in its thermal and fast reactors. Russia's VVER-1000 reactors are likely to be the first of Russia's thermal reactors to be loaded with MOX fuel. For this to be realized, further development of MOX-fuel-production technology, including fabrication of press powder with highly homogeneous plutonium distribution, is needed. At the same time, MOX fuel based on both weapon-grade and regenerated from VVER-440 SNF plutonium types has been already tested successfully in fast breeder reactors (BN-600 and BOR-60).

4.2.4 Handling SNF in Northwest Russia

The northwestern region of Russia has the highest concentration of nuclear reactors in the world. A large quantity of SNF has accumulated in the region. Defueled reactor compartments from decommissioned nuclear-powered submarines (NPSs) are also stored in the region for long periods, moored in bays along the Kola Peninsula. At the same time, storage facilities built mostly in the 1960s to store SNF and radioactive waste are in an unsatisfactory state. Work is needed to

- improve and introduce safe techniques and facilities for unloading SNF from floating NPSs;
- develop safe techniques for management, long-term storage, and final disposal of reactor compartments from decommissioned nuclear-powered ships;
- develop management technologies for treatment of SNF from NPSs with liquid-metal coolant;
- develop dismantling technologies for NPSs with damaged reactor compartments; and
- build a regional underground facility for radioactive waste storage and a centralized storage facility for long-term storage of unreprocessible SNF.

4.2.5 Managing Liquid HLW

Large amounts of liquid HLW have accumulated at the Minatom radiochemical enterprises. These wastes present serious hazards in the case of accidents or terrorist acts.

Progress has been made in immobilizing HLW from defense and commercial programs, but problems remain. These wastes have highly varied physical properties and chemical composition (e.g., sludge fraction and salt composition) so several technologies may be necessary to deal with the different components. Development of efficient technologies for processing of different types of liquid HLW is needed. This includes sludge-removal techniques for underground tanks. One approach to better matching waste forms and HLW streams is to divide (fraction-

ate) the constituents of HLW, separating the actinides and other radioisotopes into groups with different half-lives.

Work is needed to develop processes for solidification and incorporation of HLW into durable glass-like and crystalline waste forms. This research would seek, select, and develop fabrication technologies for synthesis of highly durable glass-like, glass-crystalline, and crystalline matrices for immobilization of different types of HLW, radioisotopes with similar characteristics, and individual radionuclides. Also needed are studies on the properties of composite materials obtained with different technologies (cold pressing and sintering, cold crucible melting, self-propagating high-temperature synthesis) for selection of the appropriate technology and optimization of the industrial scale fabrication process.

4.2.6 Long-Term Storage of Spent Nuclear Fuel

The available reserve capacity for reprocessing in Russia is insufficient for reprocessing the growing SNF inventory. This implies that long-term storage will be needed. Several nuclear power plants with RBMK reactors are running out of storage space for their SNF. There are no plans at this time to ship RBMK SNF from the sites, so additional storage capacity is needed. Adding dry storage for the older SNF would likely be less expensive than expanding the wet storage facilities and would free up space in the cooling pools for freshly discharged SNF, which requires wet storage. Russia will need to expand the storage facility at the Krasnoyarsk MCC facility to accept 9,000 tons of SNF, including that from VVER-1000 reactors. Research is needed to determine time limits for wet storage and to substantiate dry-storage technology with the objective to replace wet storage with dry storage where possible.

4.2.7 Excess U.S. Weapons Plutonium Without a Clear Disposition Path

At least 2 tons of excess weapons plutonium that DOE formerly planned to immobilize have been declared to be of low enough quality (“dirty”) that they cannot follow the new planned disposition path (in Section 2.2) for surplus weapons-grade plutonium and no alternative disposition path has been identified. The actual quantity of this material should be clarified and a disposition path (a method for disposal) should be found for it.

4.2.8 Disposal

Work is needed to improve existing disposal practices and planning and implementation for the whole disposal system, including transportation and disposal.

Continue detailed studies and repository design for waste disposal at Mayak and Krasnoyarsk

Russia plans to dispose of solidified HLW at PA "Mayak" and at the Krasnoyarsk MCC. The final selection of sites suitable for disposal of HLW, given the highly damaged tectonic structures in these regions, can be made only after obtaining results of some specialized studies that will enable planners to obtain projections about the geodynamic conditions at the locations far in the future. These detailed studies and design activities should continue.

Study isolation of waste injected into deep horizons

Deep well injection disposal is used for low- and intermediate-level waste generated by the radiochemical facilities at Krasnoyarsk, Tomsk, and Dmitrovgrad. Previous investigations (Compton et al. 2000; Parker et al. 1999, 2000; Malkovsky et al. 1999) predict that low- and intermediate-level wastes disposed by injection into the deep, hydraulically isolated aquifers are not likely to reach the biosphere for 1,000 years. If these appraisals are correct, then this approach provides safe disposal for wastes that decay to safe concentrations and quantities in that time. Despite the predictions of isolation, many in the United States and Europe remain skeptical about the practice of deep injection and believe that it should not continue, even with continuous environmental monitoring. Given such disagreements, international teams should continue to study the issue, conducting a comprehensive investigation of the isolation capabilities of the existing disposal wells for liquid radioactive wastes. Meanwhile, Russia should not dispose of high-activity, long-lived wastes as it exhausts the capacity of the existing wells, and Russia should conduct continuous environmental monitoring at these injection sites.

A plan for a deep geologic repository, but little work on transportation of waste to the repository

Extensive planning must be done for the transportation of SNF to a geologic repository at Yucca Mountain, including working with the states and communities along the routes. The need for such planning has been confirmed by the support of several agencies, including the U.S. Department of Transportation and DOE, for a new National Academies study of such transport issues. Participation of states and communities in this planning is important not only because of technical and logistical issues and the need for emergency response but also to begin to build understanding, and possibly acceptance, of DOE's plans.

4.2.9 Waste Management Strategy

Both the United States and Russia have many programs to deal with SNF and radioactive waste. Development of an integrated strategy should be a high priority. Without such a strategy, resources will be wasted and both safety and proliferation hazards will be left unaddressed. In both countries, an integrated strategy should be developed to incorporate, as noted above, all fuel cycle elements up to the final stages. A strategy for the waste management elements should include identification, stabilization, development of necessary facilities, transportation, and both interim and final end points. See Sidebar 4.2 for an example of an integrated approach.

4.3 AREAS FOR COLLABORATION

Both Russia and the United States have aging nuclear workforces and few replacements. A critical problem for both the Russian Federation and the United States is how to assure the availability of both the current and future supply of expert scientists, engineers, and technicians needed to work on the problems related to management of SNF and HLW. Research and development concerning processing and disposal of HLW and SNF are needed to design and then implement the new strategies that will be required if we are to improve management and disposal of these materials. Significant advances are also needed in areas related to cleanup activities in both nations.

Both Russia and the United States face serious challenges in attracting, training, and retaining the next generation of workers

SIDEBAR 4.2 An Integrated Approach

The committee recommends an integrated approach to planning management of SNF and HLW. Below is an example of the elements of a radioactive waste management program.

1. Overall objective
   a. Remediation, fuel cycle management, and disposal
   b. Waste minimization
   c. Cost minimization
   d. Societal acceptance of the program
2. Strategy (Disposal/staged disposal)
   a. Cleanup (remediation)
   b. Fuel-cycle management
   c. Combination
3. Definition of essential elements
   a. Classes of waste
   b. End points (disposal and staged disposal)
   c. Different waste forms
   d. Sources of waste
   e. Pathways
4. Constraints and boundary conditions
   a. Physical and chemical laws
   b. Society's laws
   c. Transportation and handling
   d. Funds/resources
5. Action plan with alternatives
   a. Costs, risks, and benefits of each alternative
   b. Path forward
6. Implementation
   a. Cleanup and remediation steps
   b. Fuel-cycle management steps
7. Implementation concepts
   a. Partial or full recycle
   b. Partition-separation and transmutation
   c. Decay-heat management

All of the elements in categories 2-7 should be designed to achieve or support the overall objectives. For example, under implementation, transmutation could be used to destroy the waste constituents that typically cause the greatest long-term hazard in a repository: the abundant transuranic elements, Np, Pu, Am, and Cm, and two long-lived fission products, Tc and I.

Also under implementation, because decay heat controls much of HLW-repository design, one might consider separating high-heat and low-heat radionuclide fractions. Most of the high-heat fraction is due to five elements: two fission products (Sr-90 and Cs-137), which dominate in the early centuries, and three actinides (Pu, Am, and Cm), which

continues on next page

Control the millennia that follow. The two fractions could be disposed of separately. If the low-heat fraction were acceptable for disposal as intermediate-level waste, disposal could be less expensive. If done in conjunction with transmutation, much of the actinide inventory could be destroyed in power reactors. The shorter-lived high-heat radionuclides, Sr and Cs, would be either stored until they decayed to low levels or disposed of in a special repository, which would be designed for short-lived, high-heat fractions.

that must address problems related to management of SNF and HLW. Science and engineering related to these problems advanced under government sponsorship during the Cold War, so there is now a body of knowledge from which to draw. But few young scientists and engineers are specializing in these areas, which will make progress slow and difficult. One indicator of the supply of relevant scientists and engineers in the United States is the number of students graduating from colleges and universities with bachelors and masters degrees in nuclear engineering who are trained in areas related to fission. This number declined steadily in the 1990s: Between 1992 and 1999, the number of undergraduate students enrolled in nuclear engineering dropped 72 percent, and the number of master's students dropped 46 percent (Was and Martin 2000). During a slightly shorter period, the number of Ph.D. students dropped by 29 percent (Feidberg and Kazimi 1998). Now the new availability of bachelor's and master's graduates in these areas is approximately 150 per year in the United States (Was and Martin 2000). The outlook for production of Ph.D.s in nuclear chemistry of the actinides has been even worsethan in nuclear engineering (see Hoffman 1994). Nuclear engineering and nuclear chemistry are not the only fields in which future workers on SNF and HLW problems are trained, but the committee has informally observed a similar pattern in relevant specialties in other fields, making the prospects for research in these areas discouraging.

The situation is even more alarming when one looks at workers and technicians charged with carrying out the activities. Well-trained workers who carry out their jobs with skill constitute a crucial element of safe operations. Newer and better equipment can reduce the set of possible accidents and can mitigate the consequences of such accidents, but skilled workers who know the equipment well make fewer errors, and their role in safety increases as equipment in Russia and in the United States ages and becomes less reliable. The committee observed on a visit to PA "Mayak" that the organization relies on workers and managers

with decades of experience to operate facilities that show their age.

The United States has faced these problems for many years, but as the numbers of U.S. citizens going into relevant fields such as actinide and separations chemistry, nuclear engineering, and radioecology has diminished, the United States has had the resources to import talent from other countries. This strategy may, however, be unsustainable. Russia faces greater challenges, because people trained in the relevant disciplines often have better economic opportunities in other countries (such as the United States) or in other lines of work in Russia, such as business or computer applications.

The private sector and in particular the nuclear power field is one resource to look to for stimulating employee interest in nuclear fuel and waste management. The nuclear power field is the largest employer of nuclear professionals in most countries that have nuclear power plants. If the focus is put on nuclear energy systems rather than the separate parts of these systems, then the spent nuclear fuel and nuclear waste management activities are but an integral part of the total nuclear energy system. This might attract more students and future professionals to management of nuclear waste. Thus, greater collaboration between nuclear power plant professionals and nuclear waste professionals could result in programs and activities to attract students and employees to better cover the entire nuclear energy system.

Nuclear industries anticipate the greatest demand for workers will be for nuclear engineers and health physicists, and specialists in protecting people and the environment from damaging effects of ionizing radiation. The nuclear power industry has decades of experience in satisfying personnel needs, so it could serve as a resource and a collaborator in ensuring a future workforce.

The committee has not examined options for addressing problems related to the workforce, but individual members' experience suggest some measures that might be effective:

(1) Federal governments in both countries could encourage both professors and students in these areas with endowed chairs, student fellowships, and other incentives.

(2) In Russia, jobs working on these problems (and in support of work on these problems) could be made more attractive (eco-

nomically or in other ways) to encourage outstanding people at the plants to stay in their positions and help in the training of the next generation.

(3) Internships at the various installations, and prizes and incentives for younger people might help to alleviate the current loss of bright and outstanding students ("brain drain") to other professions and other countries.

(4) In both countries, the few institutions that support student training and research in relevant disciplines should receive stable and adequate support so that we do not lose the capability to build the expert workforce.

DOE has taken a step to improve the situation in the United States with the recent creation of the Stewardship Science Academic Alliances program. More such steps will be needed in both nations.

Russia and the United States can collaborate on several other important topics of mutual concern:

- protecting materials useful in nuclear and radiological weapons;
- consolidation of nuclear materials in a few reliably protected sites;
- counter-terrorism studies and methods;
- development and refinement of technologies for safe and efficient defueling, dismantling, and disposing of decommissioned nuclear-powered submarines;
- handling the legacy wastes from nuclear-weapons production;
- transportation of spent nuclear fuel;
- development of standard, highly durable waste forms for immobilization of different types of HLW;
- methods and techniques for extraction of HLW that has been stored in tanks for decades;
- development of unified approaches to selection of geological media and sites for the HLW and SNF long-term storage and disposal; and

- research and development on methods of processing SNF that produce much less radioactive waste than the PUREX process.

In light of the terrorist attacks that have occurred in the last few years, it is worth reiterating one of the above areas for collaboration, for emphasis. Russia and the United States should prioritize working together to protect nuclear facilities from thefts of nuclear materials and from terrorist acts. The threats are present and the dangers are significant, so action should be taken without delay.

These activities require significant resources. Because funds as well as knowledgeable people are limited, resources should be allocated to the most critical problems first.

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Appendix A
Statement of Task

The objective of this study is to provide an analysis of the management of spent nuclear fuel and high-level radioactive waste in Russia and a scientific/technical assessment of the end points for this material, including options for both interim storage and permanent disposal. The study will

(1) provide a clear description of the current status of efforts to manage the inventories of spent fuel and high-level waste, including a description of waste locations, volumes, and concentrations;

(2) compare the status of efforts to manage this waste with efforts in the United States; and

(3) provide a scientific/technical assessment of end-point options for interim storage or permanent disposal of this waste.

The study was requested and funded by the U.S. Department of Energy through its Office of Civilian Radioactive Waste Management.

Appendix B
Acronyms and Abbreviations

AMB	graphite-moderated, water-cooled reactors (early versions of the RBMK reactor)
ANL	Argonne National Laboratory
ATW	accelerator transmutation of waste
BN-600	liquid metal fast reactor
BWR	boiling-water reactor
Bq	becquerels, 1Bq = 1 disintegration per second
Ci	curies, 1 Ci = 3.7×10^{10} disintegrations per second = 3.7×10^{10} becquerels
DOE	U.S. Department of Energy
DWPF	Defense Waste Processing Facility at the Savannah River Site
EURT	Eastern Urals Radioactive Trail
FTB	floating technical base
GWe	gigawatts electric
HEU	highly-enriched uranium
HLW	high-level radioactive waste
HTGR	high-temperature gas reactor
ICPP	Idaho Chemical Processing Plant
INEEL	Idaho National Engineering and Environmental Laboratory
IPPE	Institute of Physics and Power Engineering
LLW	low-level radioactive waste
LMFBR	Llquid-metal fast breeder reactor
LMR	liquid-metal reactor
LRW	liquid radioactive waste
MCC	Mining and Chemical Combine, Minatom Ministry of Atomic Energy of the Russian Federation
MOX	mixed oxide (uranium-plutonium)
MPC&A	materials protection, control, and accounting
MSRE	Molten Salt Reactor Experiment

MTHM	metric tons of heavy metal
MWd/kgHM	megawatt-days per kilogram of heavy metal
MWe	megawatts electric
MWth	megawatts thermal
NIIAR	Scientific Research Institute of Nuclear Reactors (Dmitrovgrad)
NIKIET	Research and Development Institute of Power Engineering (Moscow)
NPS	nuclear-powered ship
ORNL	Oak Ridge National Laboratory
PA “Mayak”	Production Association “Mayak”
PFS	Private Fuel Storage
PIMCA	The Priargunsky Industrial Mining-Chemical Association
PIS	the pilot-industrial site at Dmitrovgrad
PMDA	U.S.-Russia Plutonium Management and Disposi tion Agreement
PUREX	plutonium uranium extraction (chemical separation process)
PWR	pressurized-water reactor
R&D	research and development
RBMK	graphite-moderated, water-cooled reactor
REDOX	reduction-oxidation (chemical reactions)
RT-1	reprocessing facility at PA “Mayak” in Russia
RT-2	planned reprocessing facility at Zheleznogorsk in Russia
SCC	Siberian Chemical Combine (Tomsk-7 or Seversk)
SFA	spent fuel assembly
SNF	spent nuclear fuel
SPZ	sanitary-protection zone
SRS	Savannah River Site
SRW	solid radioactive waste
STB	shore technical base
TBP	tributyl phosphate
THOREX	thorium extraction (chemical separation process)
TMI	Three Mile Island (nuclear power plant in the United States)
TRUEX	Transuranic Extraction Process
TUK-104	spent fuel transport cask
VVER	Russian pressurized water reactor
WIPP	Waste Isolation Pilot Plant

APPENDIX C
Committee Member Biographies

Co-Chairs

John F. Ahearne is the director of the Ethics Program at the Sigma XI Center for Sigma XI, The Scientific Research Society, a lecturer in public policy, an adjunct professor in civil and environmental engineering at Duke University, and an adjunct scholar at Resources for the Future. His professional interests are reactor safety, energy issues, resource allocation, and public policy management. He has served as commissioner and chairman of the U.S. Nuclear Regulatory Commission, system analyst for the White House Energy Office, deputy assistant secretary of Energy, and principal deputy assistant secretary of Defense. He is a member of the National Academy of Engineering. He received his B.S. and M.S. degrees from Cornell University and a Ph.D. in physics from Princeton University.

Nikolai P. Laverov is vice president of the Russian Academy of Sciences and director of the Institute of Geology of Ore Deposits, Petrology, Mineralogy, and Geochemistry. He has worked in and with the Russian government on a range of ecological problems, particularly nuclear waste disposal. Dr. Laverov has held a variety of administrative positions, including chief of the Scientific Research Organizations Administration, which oversees the work of the Ministry of Geology's subordinate institutes. In 1992, he was named co-chair of the Earth Science Joint Working Group, which is under the auspices of the U.S.-Russian Space Agreement. He is also a member of the Council on Science and Technology under the President of the Russian Federation. Dr. Laverov graduated from the M.I.Kalinin Nonferrous Metals and Gold Institute in Moscow in 1954 and earned a doctorate in geological-mineralogical sciences in 1958. He is an academician of the Russian Academy of Sciences.

Committee Members

Rodney C. Ewing is a professor in the Department of Nuclear Engineering and Radiological Sciences with joint appointments in the Departments of Geological Sciences and Materials Science & Engineering at the University of Michigan. Prior to arriving at Michigan, Dr. Ewing was Regents' Professor in the Department of Earth and Planetary Sciences at the University of New Mexico for 23 years. His professional interests are in mineralogy and materials science, and his research has focused on radiation effects in complex ceramic materials and the long-term durability of radioactive waste forms. He is president of the Mineralogical Society of America. Dr. Ewing received M.S. and Ph.D. degrees in geology from Stanford University.

B. John Garrick is president of Garrick Consulting and was a cofounder of PLG, Inc., an international engineering, applied science, and management consulting firm formerly in Newport Beach, California. He retired as president and chief executive officer in 1997. His professional interests involve risk assessment in fields such as nuclear energy, space and defense, chemicals and petroleum, and transportation. He is a past president of the Society for Risk Analysis. Dr. Garrick is a member of the National Academy of Engineering, and of the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste. Dr. Garrick received his B.S. degree in physics from Brigham Young University and his M.S. and Ph.D. degrees in engineering and applied science from the University of California, Los Angeles, and is a graduate of the Oak Ridge School of Reactor Technology.

Darleane C. Hoffman is professor of the graduate school in chemistry at the University of California, Berkeley, and charter director and senior advisor of the Glenn T. Seaborg Institute for Transactinium Science at Lawrence Livermore National Laboratory. She is currently co-leader of the Heavy Element Nuclear & Radiochemistry Group at Lawrence Berkeley National Laboratory, where she is a faculty senior scientist. Dr. Hoffman's research is in the field of atom-at-a-time studies of the nuclear and chemical properties of the transfermium elements, spontaneous fission properties, and studies of radionuclide migration in the environment. Dr. Hoffman was awarded the U.S. National Medal of Sci-

ence in 1997 and the American Chemical Society's highest honor, the Priestly Medal, in 2000. Dr. Hoffman received a B.S. and a Ph.D. in physical chemistry from Iowa State University.

George M. Hornberger is associate dean for the sciences and Ernest H. Ern Professor of Environmental Sciences at the University of Virginia, where he has taught since 1970. His research concerns the effects of hydrological processes on transport of dissolved and suspended constituents through catchments and aquifers. Dr. Hornberger is a member of the National Academy of Engineering. He was appointed to the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste in 1996 and currently serves as chair of the committee. Dr. Hornberger received his B.S. and M.S. degrees from Drexel University in 1965 and 1967, respectively. In 1970, he received a Ph.D. in hydrology from Stanford University.

Nikolay N. Melnikov is director of the Mining Institute of the Kola Science Centre of the Russian Academy of Sciences. He has worked on a range of underground civil construction and underground space problems, including emplacement of nuclear power facilities and radioactive waste management and disposal. Professor Melnikov has three years of research experience in Canada and has been a leader of international projects on radioactive waste management with companies in Germany, France, Belgium, Norway, and Finland, especially on the Tacis program under the European Commission. Author of over 200 published works, professor Melnikov graduated from the Moscow Mining Institute in 1960 and earned a doctorate in science (engineering) in 1974 and professor's diploma in 1977. He is an academician of the Russian Academy of Sciences.

Boris F. Myasoedov is deputy secretary general for science of the Russian Academy of Sciences and chief of the Radiochemical Laboratory of V.I. Vernadsky Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences. His scientific activity covers such fields as fundamental chemistry of actinides, fuel reprocessing, partitioning of radioactive waste, and environmental protection. He is an author of more than 450 publications, including monographs. Academician Myasoedov graduated

from D.I. Mendeleev Chemical-Technology Institute in Moscow in 1954 and earned a doctor of chemistry in 1965.

Alexander A. Pek is head of the section of mathematical modeling in the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry of the Russian Academy of Sciences. His field of scientific activity includes modeling of ore-forming system evolution, studies on heat and mass transport in heterogeneous rocks, and investigation of contaminant transport in geological media. He is author or co-author of more than 150 works. Dr. Pek graduated from the Polytechnical Institute in Novocherkassk, defended Ph.D. thesis in 1966, and obtained the second degree (doctor of sciences) in 1983.

APPENDIX D
Presentations and Site Visits

First Committee Meeting: October 14-16, 2001

Cecil and Ida Green Building, National Research Council
2001 Wisconsin Avenue NW, Washington, DC 20007 USA

TUESDAY, October 16, 2001

DOE comments to the committee	Jeff Williams (OCRWM, DOE)
Overview of wastes at the Savannah River Site	Lucien Papouchado (WSRC SRS)
Overview of wastes at the INEEL	Michael Worley (EM-41, DOE)
Overview of wastes at the Hanford site	Roy Gephart (PNNL)
Overview of civilian spent nuclear fuel	John Vincent (NEI)
Plans for disposal at Yucca Mountain	William Boyle, (DOE YMP)
Plans for disposal at the WIPP	Dr. Clayton Gist (DOE Carlsbad Office)

Site Visit:
October 18, 2001.
Waste Isolation Pilot Plant, Carlsbad, New Mexico, Committee members N.N. Melnikov, B.F. Myasoedov, A.A. Pek, and committee staff.

Second Committee Meeting: March 25-26, 2002

President's Hall, Russian Academy of Sciences
Moscow, Leninsky Prospekt, 32a 2nd floor – Russia

MONDAY, March 25, 2002

Spent nuclear fuel, high-level radioactive wastes, and nuclear energy and their future in Russia	Prof. M.I. Solonin Minatom, VNIINM, Director
Overview of SNF and HLW at Mayak	Dr. P.P. Shevtsev, Minatom, PA "Mayak", Central Factory Laboratory, Head of SNF reprocessing group
Overview of SNF and HLW at Krasnoyarsk	Dr. G.K. Dobrynskikh Minatom, MCC, Deputy Head of Technical Division.
Overview of Naval spent nuclear fuel	Academician N.N. Melnikov, RAS, Kola Scientific Center, Director of the Mining institute
Radioisotope fractionation in implementation of a closed nuclear fuel cycle.	Academician B.F. Myasoedov, RAS, GEOKHI, Head of Radiochemical Laboratory
Examination of geological, environmental, and societal aspects of the proposed storage facility at the Priargunsky MCC	Prof. V.A. Ovseichuk, Minatom, Priargunsky MCC, Director of Science

TUESDAY, March 26, 2002

MOX fuel-fabrication technology and MOX fuel utilization in implementation of a closed nuclear fuel cycle	Prof. V.V. Volk, Minatom, VNIINM, Deputy General Director

Site Visits:

March 27-29, 2002.

Production Association “Mayak”, Ozersk, Chelyabinsk. Committee members J.F. Ahearne, R.C. Ewing, and D.C. Hoffman, and committee staff.

Scientific Research Institute of Atomic Reactors, Dmitrovgrad and A.A. Bochvar All-Russian Scientific Research Institute of Inorganic Materials. Committee member B.J. Garrick and committee staff.

APPENDIX E
Laws Governing Radioactive Waste of the United States and Russia

THE UNITED STATES OF AMERICA

Laws[1, 2]

Nuclear materials, power, and wastes

Atomic Energy Act (As Amended) Atomic Energy Act of 1954, P.L. 83-703; U.S.C. 2011-2282
Energy Reorganization Act of 1974, P.L. 93-438
Low-Level Radioactive Waste Policy Act as amended in 1985 (42 USC 2021b et. seq.)
Nuclear Waste Policy Act of 1982, Public Law 97-425
Nuclear Waste Policy Amendments Act of 1987, Title Iv, Subtitle A of Public Law 100-203, The Omnibus Budget Reconciliation Act of 1987
Waste Isolation Pilot Plant Land Withdrawal Act as amended in 1996 (PL 102-579)
The 1996 WIPP LWA Amendments (PL104-201)
Energy Policy Act of 1992, Public Law 102-486; 33 U.S.C. 1251-1387
Hazardous Materials Transportation Uniform Safety Act of 1990, As Amended, Public Law 101-615

[1] See, e.g., U.S. Nuclear Regulatory Commission. 2002. Nuclear Regulatory Legislation, 107th Congress; 1st Session. Office of the General Counsel, NUREG-0980 Vol. 1, No.6. and Congressional Research Service. 2002. Summaries of Environmental Laws Administered by the EPA. Report RL30022.

[2] P.L. means Public Law, and U.S.C. means U.S. Code.

Uniting And Strengthening America By Providing Appropriate Tools Required To Intercept and Obstruct Terrorism (USA Patriot Act) Act of 2001, Public Law 107-56

National Defense Authorization Act For Fiscal Year 2002 Public Law 107-107 Section 3154. Annual Assessment And Report On Vulnerability of Department of Energy Facilities To Terrorist Attack

National Defense Authorization Act For Fiscal Year 2000, Public Law 106-65 Sec. 3134. Procedures For Meeting Tritium Production

Strom Thurmond National Defense Authorization Act For Fiscal Year 1999, Public Law 105-261 Sec. 3134. Licensing Of Certain Mixed Oxide Fuel Fabrication And Irradiation Facilities And Sec. 3155. Disposition Of Surplus Defense Plutonium At Savannah River Site, Aiken, South Carolina

Environmental Protection

Public Health Service Act as amended in ‘57,’58,’60, ‘76 (42 USC 201 et seq.)

Federal Water Pollution Control Act (P.L. 92-500, enacted in 1972), commonly known as the Clean Water Act (amended by P.L. 95-217 in 1977, P.L. 97-117 in 1981, and P.L. 100-4 in 1987)

Safe Drinking Water Act of 1974 P.L. 93-523 (42 U.S.C. 300f-300j; amended by P.L. 95-190, P.L. 96-63, P.L. 96-502, P.L. 99.339, P.L. 100-572, P.L. 104-182

Clean Air Act (42 USC 7401-7661; P.L. 88-206, as amended)

Clean Air Amendments of 1977 (P.L. 95-95; 91 Stat. 685).

Clean Air Amendments of 1990 (P.L. 101-549)

National Environmental Policy Act (42 U.S.C. 4321-4347; P.L. 91-190 as amended by P.L. 94-52, P.L. 94-8)

Marine Protection, Research, and Sanctuaries Act of 1972 referred to as the Ocean Dumping Act and Amendments (33 U.S.C. 1401-1445, 16 U.S.C. 1431-1447f, 33 U.S.C. 2801-2805; P.L. 92-532, P.L. 93-254; P.L. 95-153; P.L. 96-381; P.L. 96-572, P.L. 97-424, P.L. 99-272, §§6061-6065, P.L. 99-662, §§211, 728, 1172, P.L. 100-4, §508, P.L. 100-627, title I, P.L. 100-688, title I; P.L. 100-688, title III; P.L. 101-593, title III; P.L. 102-567, title V; P.L. 102-580, §§504-510

Solid Waste Disposal/Resource Conservation and Recovery Act and Major Amendments(42 U.S.C. 6901-6991k)
Resource Conservation and Recovery Act of 1976 P.L. 94-580
Solid Waste Disposal Act Amendments of 1980 P.L. 96-482
Hazardous and Solid Waste Amendments of 1984 P.L. 98-616
Federal Facility Compliance Act of 1992 P.L. 102-386
Comprehensive Environmental Restoration, Compensation, and Liability Act
Superfund and Amendments(codified generally as 42 U.S.C. 9601-9675)
Comprehensive Environmental Response, Compensation, and Liability Act of 1980 P.L. 96-510 (commonly known as Superfund)
Superfund Amendments and Reauthorization Act of 1986 P.L. 99-499
Superfund extension P.L. 101-508, § 6301, 11231
Defense Authorization Act of Fiscal Year 1997 P.L. 104-201, §334

Regulations Concerning Radiation And Radioactive Waste[3]

General

10CFR20	Part 20 Standards For Protection Against Radiation
10CFR835	Part 835 Occupational Radiation Protection
29CFR1910	Part 1910 Occupational Safety And Health Standards
40CFR141	Part 141 National Primary Drinking Water Regulations

Storage and Disposal

40CFR191	Environmental Radiation Protection Standards For Management And Disposal Of Spent Nuclear Fuel, High-Level And Transuranic Radioactive Wastes
10CFR60	Disposal Of High-Level Radioactive Wastes In Geologic Repositories
10CFR61	Licensing Requirements For Land Disposal Of Radioactive Waste
40CFR197	Public Health And Environmental Radiation Protection Standards For Yucca Mountain, Nevada
10CFR63	Disposal Of High-Level Radioactive Wastes In A Geologic Repository At Yucca Mountain, Nevada

[3] 10CFR20 means Title 10 of the Code of Federal Regulations, Part 20. Note that these are only the federal regulations; many states, by agreement with federal agencies, have authority to pass their own regulations.

10CFR72	Licensing Requirements For The Independent Storage Of Spent Nuclear Fuel, High-Level Radioactive Waste, And Reactor-Related Greater Than Class C Waste
10CFR960	General Guidelines For The Preliminary Screening Of Potential Sites For A Nuclear Waste Repository
10CFR961	Standard Contract For Disposal Of Spent Nuclear Fuel And/Or High-Level Radioactive Waste
10CFR963	Yucca Mountain Site Suitability Guidelines
40CFR194	Criteria For The Certification And Re-Certification Of The Waste Isolation Pilot Plant's Compliance With The 40 Cfr Part 191 Disposal Regulations
44CFR351	Radiological Emergency Planning and Preparedness Regulation

Transportation

10CFR71	Packaging And Transportation Of Radioactive Material
49CFR173	Shippers General Requirements For Shipments And Packagings
49CFR397	Transportation Of Hazardous Materials

Executive Orders

Establishing the Federal Radiation Council, EO 10831
Federal Emergency Management, EO 12148
Assignment of Emergency Preparedness Responsibilities, EO 12656

Presidential Decision Directives

U.S. Policy on Counter-Terrorism, PDD 39
Protection Against Unconventional Threats to the Homeland and Americans Overseas, PDD 62
Critical Infrastructure Protection, PDD 63

Federal Plans

Federal Radiological Emergency Response Plan

Federal Response Plan
National Oil & Hazardous Substances Pollution Contingency Plan, 40 CFR Part 300

THE RUSSIAN FEDERATION

Laws

The Law of the RSFSR on "Environmental Protection" # 2060-1 of 19.12.1991 (rev. 10.07.2001)
The Federal Law "On the Use of Atomic Energy", # 170-FZ of 21.11.1995 (rev. 10.07.2001)
The Federal Law "On Radiation Safety of General Public", # 3-FZ of 09.01.1996
The Federal Law "On Sanitary and Epidemiological Welfare of General Public", # 52-FZ of 30.03.1999
The Federal Law "On Environmental Review", # 174-FZ of 23.11.1995
The Federal Law "On Atmospheric Air Protection", # 96-FZ of 04.05.1999
The Russian Federation Law "On Mineral Resources", # 2395-1 of 21.02.1992 (rev. 14.05.2001)
"Water Code of the Russian Federation" of 16.11.1995, # 167-FZ
The Federal Law "On Special Environmental Programs for Rehabilitation of Areas Contaminated by Radiation", # 68-FZ of 10.07.2001
The Federal Law "On Protection of General Public and Territories from Natural and Technogenic Emergencies", # 68-FZ of 21.12.1994
The Federal Law "On Accedence of the Russian Federation to the International Convention on Liability and Indemnity Related to Marine Transportation of Hazardous and Noxious Substances of 1996", # 17-FZ of 02.12.2000
The Federal Law "On Industrial Safety of Hazardous Process Facilities", #116-FZ of 21.07.1997
The Federal Law "On Safety of Hydraulic Structures", # 117-FZ of 21.07.1997
The Federal Law "On the Specifically Protected Environmental Territories", # 33-FZ of 14.03.1995
The Federal Law "On Fire Safety", # 69-FZ of 21.12.1994

The Federal Law "On Governmental Control over International Automobile Transportation and Liability for Violations of the Relevant Procedures", # 127-FZ of 24.07.1998
The Federal Law "On Governmental Regulation of External Trade Activities", # 157-FZ of 13.10.1995
The Federal Law "On Production and Consumption Wastes", # 89-FZ of 24.06.1998
The Federal Law "On Differentiation of the Governmental Land Ownership", # 101-FZ of 17.07.2001
The Federal Law "On Payments for Use of Water Reservoirs", # 71-FZ of 06.05.1998

Orders and Directives of the President of the Russian Federation

"Additional Measures to Enforce Compliance with Environmental Safety Requirements Related to Reprocessing of Spent Nuclear Fuel", # 389 of 20.04.95
"On Executive Bodies Authorized to Regulate Safety of Uses of Atomic Energy", # 26 of 21.01.97

Orders by the Government of the Russian Federation

"On Decision-Making Procedures Concerning Siting and Construction of Nuclear Facilities, Radiation Sources and Storage Facilities", # 306 of 14.03.97
"On Approval of Procedures for Acceptance of Spent Nuclear Fuel from Foreign Nuclear Power Plants for its Further Reprocessing at the Russian Enterprises and Return of the Radioactive Waste and Materials Generated in the Course of its Reprocessing", # 773 of 29.07.95
"Modifications and Additions Introduced to the Procedures for Acceptance of Spent Nuclear Fuel from Foreign Nuclear Power Plants for its Further Reprocessing at the Russian Enterprises and Return of the Radioactive Waste and Materials Generated in the Course of its Reprocessing", # 745 of 10.07.98
"Rules for Physical Protection of Nuclear Materials, Nuclear Facilities and Storage Facilities for Nuclear Materials", # 264 of 07.03.97

"On Approval of the Provisions for Licensing Activities in the Field of Use of Atomic Energy", # 865 of 14.07.97
"On Export and Import of Nuclear Materials, Equipment and Special Non-Nuclear Materials and Relevant Technologies", # 973 of 15.12.2000
"On Approval of the List of Employee Positions at Atomic Energy Facilities who are subject to permits by the Federal Nuclear and Radiation Safety Authority for Conduct of Operations in the Field of Use of Atomic Energy", # 240 of 03.03.97
"On Approval of the Provisions for Procedure and Terms and Conditions of Levying the Use of Natural Resources, Water Areas, and Areas of the Sea Bed", # 828 of 28.10.92

Federal Standards and Rules in the Field of Use of Atomic Energy

General Provisions for Nuclear Fuel Cycle Facility Safety (OPB OYaTTs). NP-016-2000. Gosatomnadzor of Russia, 2000
Accounting of Natural and Technogenic External Impacts to Nuclear and Radiation Hazardous Facilities. PNAE G-05-035-94. Gosatomnadzor of Russia, 1995
Safety Rules for Storage and Transportation of Nuclear Fuel at Nuclear Power Facilities. PNAE G-14-029-91, Gosatomnadzor of the USSR, 1991
Collection, Reprocessing, Storage and Conditioning of Liquid Radioactive Waste. Safety Requirements. NP-019-2000, Gosatomnadzor of Russia, 2000
Collection, Reprocessing, Storage and Conditioning of Solid Radioactive Waste. Safety Requirements. NP-020-2000, Gosatomnadzor of Russia, 2000
Management of Gaseous Radioactive Waste. Safety Requirements. Gosatomnadzor of Russia, 2000
Basic Safety and Physical Protection Rules for Transportation of Nuclear Materials. OPBZ-83. GKAE of the USSR, Ministry of Internal of the USSR, Ministry of Public Health of the USSR, 1983. Concurred upon with Gosatomenergonadzor of the USSR

Federal Sanitation Rules

Basic Sanitation Rules for Operations with Radioactive Substances and Other Sources of Ionizing Radiation. OSP-72/87. Ministry of Public Health of the USSR

Basic Sanitation Rules for Radiation Safety Ensurance (BSR-SRE-99). SP2.6.1.799-99. Ministry of Public Health of Russia, 2000

Radiation Safety Standards (NRB-99). SP 2.6.1 758-99

Sanitation Rules for Management of Radioactive Waste. SPORO-85. Ministry of Public Health of the USSR, 1985

Guiding Documents of Gosatomnadzor of Russia

"The Procedures for Review by Gosatomnadzor of Russia Headquarters of Application and Documents Submitted for Getting License for Activities in the Field of Use of Atomic Energy", RD-03-08-98

"The Provisions for Review of Documents Supporting Nuclear and Radiation Safety of a Nuclear Facility, Radiation Source, Storage Facility or Quality of a Declared Activity", RD-03-13-99

"The Provisions for Qualification of Software to be Used for Justification or Ensurance of Safety at Atomic Energy Facilities", RD-03-17-94

"Basic Provisions for Preparation, Review and Making Decisions on Modifications to Design, Technological and Operating Documentation which Influence Nuclear and Radiation Safety", RD-03-019-94

"The Provisions for Development of Federal Standards and Rules in the Field of Use of Atomic Energy to be Approved by Gosatomnadzor of Russia", RD-03-23-98

"Requirements to Content and Composition of a Verification Report on Software to be Used for Justification or Ensurance of Safety at Atomic Energy Facilities", RD-03-34-2000

"Guide on Certification of Equipment, Products and Technologies for Nuclear Facilities, Radiation Sources and Storage Facilities", RD-03-35-96

"Terms and Conditions of Supply of Foreign-Made Equipment, Products and Components for Nuclear Facilities, Ra-

diation Sources and Storage Facilities of the Russian Federation", RD-03-36-97
"Requirements to Composition of Package and Contents of Documents to Support Nuclear and Radiation Safety of Activities Subject to Licensing with Regard to Fuel Cycle Enterprises and Organization Rendering Services to Fuel Cycle Enterprises", RD-05-15-97
"The Provisions for Granting Permits by Gosatomnadzor of Russia to Employee of Fuel Cycle Facilities to Conduct Operations in the Field of Use of Atomic Energy", RD-05-17-2001

Regulatory Documents Approved by Other Federal Executive Authorities

Sanitation Rules for Design of Enterprises and Facilities for Nuclear Industry. SNP-77. Minsredmash of the USSR, 1978
Basic Internal Industrial Nuclear Safety Rules for Use, Reprocessing, Storage and Transportation of Nuclear Hazardous Fissile Materials. PBYa-06-00-99. Minatom of Russia, 1996
Internal Industrial Rules for Design and Operation of Self-Sustained Chain Reaction Initiation Alarm Systems and Measures to Contain its Consequences. PBYa-06-10-99
Nuclear Safety Rules for Storage and Transportation of Nuclear Hazardous Fissile Materials. PBYa-06-09-90. Minatomenergoprom of the USSR, 1991
Safety Rules for Transportation of Radioactive Substances. PBTRV-73. Ministry of Public Health of the USSR, GKAE of the USSR, Ministry of Interior of the USSR, 1973
Radiation Safety Rules for Transportation by Rail of Spent Nuclear Fuel from Nuclear Power Plants. PRB-88. Ministry of Public Health, Minsredmash of the USSR, Ministry of Rail Transport of the USSR, 1988
Certification System for Equipment, Products and Technologies for Nuclear Facilities, Radiation Sources and Storage Facilities. Basic Provisions. Minatom of Russia, Gosstandart of Russia, Gosatomnadzor of Russia

State Standards (SS) and Internal Industrial Standards (IIS)

SS 22901-78. Packaging and Transportation Sets for Spent Fuel Assemblies of Nuclear Reactors. Types and Basic Parameters

SS 26013-83. Packaging and Transportation Sets for Spent Fuel Assemblies of Nuclear Reactors. General Technical Requirements

SS 25688-83. Spent Nuclear Fuel Transshipment Bays. General Requirements

SS 15484-81. Ionizing Radiation and Relevant Measurements. Terms and Definitions

SS 28461-82. Packaging and Transportation Sets for Spent Fuel Assemblies of Nuclear Reactors. Requirements to Nuclear Safety Calculation Methods

SS 28506-90. Fuel Assemblies of VVER Nuclear Reactors. Fuel Element Integrity Inspection Methods

IIS 95 745-95. Spent Fuel Assemblies of VVER Nuclear Power Reactors. General Requirements to Shipment to Recovery Plants

IIS 95 957-93. General Requirements to Delivery of Spent Fuel Assemblies of Propulsion Nuclear Reactors

IIS 95 10340-88. NPP Power Reactor SNFA Casing. General Requirements

IIS 95 957-93. Spent Fuel Assemblies of Ship and Marine Vehicle Nuclear Reactors. General Delivery Requirements

RD 95 10501-94. Packaging and Transportation Sets for SNF. Content and Scope of Calculation Substantiation of Radiation and Nuclear Safety