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Categorization of Used Nuclear Fuel Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy

December 2012

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Reactor and Nuclear Systems Division

CATEGORIZATION OF USED NUCLEAR FUEL INVENTORY IN SUPPORT OF A COMPREHENSIVE NATIONAL NUCLEAR FUEL CYCLE STRATEGY

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ACRONYMS

AC	Allis Chalmers
ANF	Advanced Nuclear Fuels
APSRA	axial power shaping rod assembly
B&W	Babcock and Wilcox
BPRA	burnable poison rod assemblies
BWR	boiling water reactor
CE	Combustion Engineering
COL	Combined (construct and operate) license
DOE	Department of Energy
DOE-EM	Department of Energy, Office of Environmental Management
DOE-NE	Department of Energy, Office of Nuclear Energy
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FCT	Fuel Cycle Technologies
GA	General Atomics
GE	General Electric
GNF	Global Nuclear Fuels
GWd	gigawatt-day
HEU	highly enriched uranium
INL	Idaho National Laboratory
ISFSI	independent spent fuel storage installations
LWR	light water reactor
MOX	mixed oxide
MTHM	metric ton of heavy metal
MTU	metric ton uranium
MWd	megawatt-day
NFS	Nuclear Fuel Services
NRC	Nuclear Regulatory Commission
NU	Northeast Utilities
NWTRB	Nuclear Waste Technical Review Board
PWR	pressurized water reactor
RCCA	rod control cluster assembly
R&D	research and development
RD&D	research, development, and demonstration
UFDC	Used Fuel Disposition Campaign
UNC	United Nuclear Corporation
UNF	used nuclear fuel
WE	Westinghouse Electric
wt %	weight percent

EXECUTIVE SUMMARY

The Department of Energy's Office of Fuel Cycle Technologies (FCT) in the Office of Nuclear Energy (DOE-NE) has conducted a technical review and assessment of the total current inventory [~70,150 MTHM (metric ton of heavy metal) as of 2011] of domestic discharged used nuclear fuel (UNF) and estimated that up to ~1700 MTHM of existing commercial UNF should be considered for retention to support research, development, and demonstration (RD&D) needs and national security interests. The 70,150 MTHM includes commercial (~67,600 MTHM), highly enriched uranium (HEU) (~50 MTHM), and DOE-owned (~2500 MTHM) UNF. The remainder, ~68,450 MTHM (both DOE-owned and commercial UNF) or ~98% of the total current inventory by mass, can proceed to permanent disposal without the need to ensure retrievability for reuse or research purposes. The assumptions used for this assessment are consistent with the DOE-NE R&D Roadmap;[*] specifically, the time to complete the needed RD&D places commercial reprocessing availability no sooner than the 2030 time frame. This assessment does not assume any decision about future fuel cycle options or preclude any potential options, including those with potential recycling of commercial UNF, since the ~2000 MTHM that is generated annually could provide the feedstock needed for deployment of alternative fuel cycles; for example, by 2030 an additional ~40,000 MTHM of commercial UNF will have been generated.

The technical assessment considered discharged UNF from commercial nuclear electricity generation and defense and research programs and divided the current (as of 2011) UNF inventory into the following three categories:

1. Disposal – excess material that is not needed for other purposes;

2. Research – material needed for RD&D purposes to support waste management (e.g., UNF storage, transportation, and disposal) and development of alternative fuel cycles (e.g., separations and advanced fuels); and

3. Recycle/Recovery – material with inherent and/or strategic value.

As a result of consideration of RD&D needs within the DOE-NE programs, time frames in which recycle fuel cycles could be deployed, projections for electricity and nuclear growth, and possible uses to support national security interests, it is proposed that the vast majority of the total UNF inventory should be placed in the first category and permanently disposed, without the need to make fuel retrievable from disposal for reuse or research purposes. It is proposed that material in the latter two categories should be retained to support ongoing and planned RD&D needs and national security interests. The amount of material designated for retention includes a sufficient margin to provide assurance that future retrievability from disposal will not be necessary for reuse or research purposes.

Key tenets and assumptions used in this technical assessment include the following.

1. Access to some amount of UNF is needed to support RD&D for the DOE-NE FCT program objectives related to UNF management and alternative fuel cycles.

2. The two principal options for addressing UNF management are geologic disposal and recycling.

3. U.S. nuclear power plants will continue to discharge ~2000 MTHM annually for the next couple of decades; projections beyond the next couple of decades are less certain.

[*] *Nuclear Energy Research and Development Roadmap*, Report to Congress, U.S. Department of Energy, Office of Nuclear Energy, Washington, DC, April 2010, http://www.ne.doe.gov/pdfFiles/NuclearEnergy_Roadmap_Final.pdf.

4. The option of recycling commercial UNF at a future date is maintained, pending a decision.

5. Although fuel recycling depends on future decisions, it is assumed that industrial-scale (100s to 1000s of MTHM/y) recycling of commercial UNF is unlikely to begin for at least 20 years (2030 time frame), at which time an additional ~40,000 MTHM of UNF will have been discharged.

6. Recycling in any potential future alternative fuel cycle would likely be designed and optimized for the material needs of the associated reactor fleet based on the current and projected UNF discharges and inventory at that time, rather than UNF feedstock that is no longer being produced.

7. The time frame for the development of alternative fuel cycles is assumed to be consistent with the schedule in the DOE-NE R&D Roadmap.

8. It is assumed that the transportation and placement of the current UNF inventory in disposal is unlikely to begin for at least 10 years and will take several decades.[*]

The current inventory of domestic UNF is massive, diverse, dispersed, and increasing. Approximately 67,600 MTHM of commercial UNF, representing a total of ~23 billion curies of long-lived radioactivity,[†] ~2500 MTHM of DOE-owned UNF, and ~50 MTHM of HEU UNF are currently stored at 79 sites in 34 states. The commercial UNF inventory is currently increasing annually by ~2000 MTHM[‡] and will increase at a greater rate in the future if nuclear power generation increases. Reactor and fuel designs, as well as reactor operating conditions, have evolved in the United States since the first commercial development of nuclear power, resulting in considerable variation in the characteristics (e.g., fuel assembly and cladding materials, initial enrichment, discharge burnup, and irradiation exposure conditions) of the current UNF inventory. These variations may raise issues with aspects of nuclear fuel management, for example, demonstrating compliance with storage, transportation, and disposal regulatory criteria for all the variations present in the current UNF inventory.

The technical assessment of the domestic UNF inventory included a set of attributes relative to permanent geologic disposal, UNF research needs, deployment of alternative fuel cycles, and national security materials strategy and then used the attributes to categorize the current UNF inventory. Attributes considered include isotopic compositions (e.g., fissile and non-fissile content), physical and material characteristics that impact recycling and/or disposal facility design and operations (e.g., accessibility of material, diversity of material, condition of material, and material hazards), national security materials strategy, and current and projected RD&D needs to support UNF management and alternative fuel cycle development. Consideration was given to the fact that since the United States is generating ~2000 MTHM annually, disposal of the majority of the current commercial UNF does not preclude the option of recycling commercial UNF at a future date. For example, assuming the current discharge rate remains constant, if the United States built and began operation of an industrial-scale reprocessing facility with annual capacity of up to 2000 MTHM by 2030 that used 5-year-cooled fuel, a portion of the discharged UNF would not need to be retained to support this facility until 2025.

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[*] *Spent Nuclear Fuel: Accumulating Quantities at Commercial Reactors Present Storage and Other Challenges*, GAO-12-797, U.S. Government Accountability Office, August 2012.

[†] J. T. Carter, A. J. Luptak, and J. Gastelum, *Fuel Cycle Potential Waste Inventory for Disposition*, FCR&D-USED-2010-000031 REV 5, U.S. Department of Energy, July 2012.

[‡] *Effects of a Termination of the Yucca Mountain Repository Program and Lessons Learned*, GAO-11-229, U.S. Government Accountability Office, April 2011.

An example projection of the identified material for disposal and retention (research and recycle) on a per-decade basis is provided in Figure ES-1. This figure shows the total current UNF inventory in 2011 and designates all but ~1700 MTHM for disposal. For UNF generated in subsequent decades, the figure identifies the material for disposal and retention assuming a constant discharge rate of 2000 MTHM/y and a recycling strategy implemented by 2030. Note that UNF is systematically retained for RD&D purposes prior to 2025, after which the UNF is retained principally for recycling. This example is just one possible scenario and is only provided to illustrate the point that disposal of the current UNF inventory will not adversely impact deployment of an alternative fuel cycle in the future, even for a recycle fuel cycle.

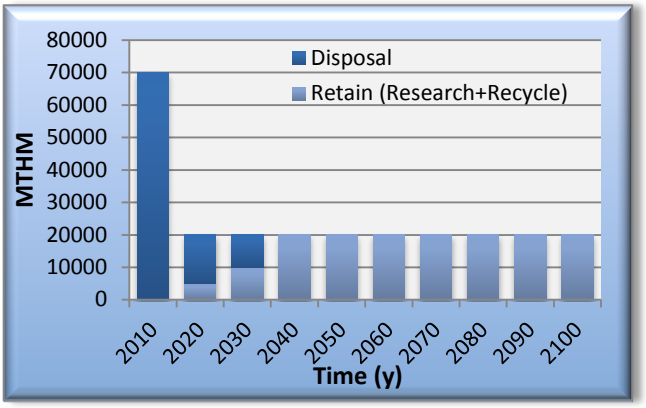

Figure ES-1. Categorization of UNF assuming current discharge rate and recycling beginning in 2030.

Based on the technical assessment, ~68,450 MTHM or ~98% of the total current inventory by mass, can proceed to permanent disposal without the need to ensure retrievability for reuse or research purposes.

Execution of the DOE-NE's Office of FCT mission* requires immediate and continued access to select UNF material for research purposes. Access to this material is needed to support the development of the safety basis for extended storage of commercial UNF and transportation following extended storage periods (e.g., commercial UNF with varying cladding materials and exposure conditions may be needed to address long term fuel integrity) and disposal (e.g., a range of uranium oxide fuel may be needed to demonstrate how UNF degrades in various environments). Additionally, access to material is needed for RD&D to support development of potential future alternative fuel cycles. As recommended by the Blue Ribbon Commission on America's Nuclear Future,† fuel cycle R&D activities are critical to maintaining "Active U.S. leadership in international efforts to address safety, waste management, non-proliferation, and security concerns."

HEU UNF may be useful to support national security missions and represents a small fraction of the current UNF inventory (up to ~50 MTHM). This material represents U.S.-origin enriched uranium that is not subject to international consent agreements. For example, it could be used to offset the need for a dedicated enrichment plant to support national security missions. Given the special nature of this material, it is recommended that a study be conducted to evaluate the benefits of recovering this material.

In conclusion, an assessment of the UNF inventory and the RD&D needs has estimated that access to ~1700 MTHM of the existing commercial UNF inventory should be retained to support the DOE-NE FCT mission. The quantity was determined based on projected RD&D needs and practical considerations for access to a sufficient quantity of representative samples of the diverse commercial UNF inventory to

*"to develop used nuclear fuel management strategies and technologies to support meeting federal government responsibility to manage and dispose of the nation's commercial used nuclear fuel and high-level waste; develop sustainable fuel cycle technologies and options that improve resource utilization and energy generation, and reduce waste generation, enhance safety, and limit proliferation risk."

†Blue Ribbon Commission on America's Nuclear Future, *Report to the Secretary of Energy*, January 2012, http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf.

support UNF storage, transportation, and disposal; access to high-burnup UNF representative of future discharges in quantities sufficient to support fuel cycle technology development; and a sufficient margin to provide assurance that future retrievability from disposal will not be necessary. The main conclusion of this assessment is not the specific amounts or specific assemblies for retention and disposal but rather that access to some small fraction of the existing UNF should be retained, while the remainder can proceed to disposal without the need to ensure retrievability for reuse or research purposes. Because a repository is not anticipated to be available for more than a decade, time is available to refine, if needed, the specific amounts and select specific assemblies as the RD&D programs proceed and the associated UNF material needs are better defined.

Finally, note that categorization of UNF for disposal does not require a determination that it has no value. In principle, all irradiated fuel has some potential value as an energy source. The determination instead supports a comprehensive national fuel cycle strategy.

ACKNOWLEDGMENTS

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1. INTRODUCTION

This report documents a technical review and assessment of the current inventory of domestic discharged used nuclear fuel (UNF) in support of a comprehensive national nuclear fuel cycle strategy. The objective of the review and assessment is to determine if the domestic UNF inventory can be separated into different, distinguishable categories relative to disposition options and, if so, to quantitatively differentiate the UNF inventory relative to the defined categories. This assessment is consistent with the Department of Energy Office of Nuclear Energy's (DOE-NE) Fuel Cycle Technologies (FCT) Office mission,[1] "to develop used nuclear fuel management strategies and technologies to support meeting federal government responsibility to manage and dispose of the nation's commercial used nuclear fuel and high-level waste; develop sustainable fuel cycle technologies and options that improve resource utilization and energy generation, and reduce waste generation, enhance safety, and limit proliferation risk," and is motivated by the recognition that characterization and categorization of the domestic UNF inventory can inform decisions relative to domestic disposition options and UNF management. For example, if a certain fraction of the UNF inventory is determined to be excess material that is not needed for other purposes, that information can clarify needs for geologic disposal, such as capacity and retrievability, as well as impact how and where that material is handled and stored in the future. Alternatively, if a certain fraction is determined to be useful for recycling, that knowledge can clarify needs for future reprocessing facilities, such as capacity and other facility characteristics, as well as how and where the UNF is handled and stored, including the importance of assembly integrity and retrievability. The scope of this assessment includes the current (as of 2011) inventory of discharged UNF from commercial nuclear electricity generation and defense and research programs.

The current inventory of domestic UNF is massive, diverse, dispersed, and increasing. Although the UNF inventory has been and continues to be managed safely, it represents a significant financial liability. The two principal options for addressing UNF management are geologic disposal and recycling, which also requires geologic disposal for resulting high-level waste. Given the current mass [~70,150 MTHM (metric ton of heavy metal)] and diversity of the domestic UNF inventory and the fact that U.S. nuclear power plants are discharging ~2000 MTHM annually, it is difficult to conceive a realistic or financially viable alternative nuclear fuel cycle in which the current inventory would need to be retained for reuse. On the other hand, geologic disposal of the entire current inventory would reduce and potentially eliminate access to UNF that may be needed to support UNF management and alternative fuel cycle research, development, and demonstration (RD&D). Therefore, the focus of this assessment is on the determination of the characteristics and amounts of UNF that should be retained for potential future use and those that should be designated for disposal.

The assessment approach includes the following:

1. Collection and analysis of current and projected UNF inventory data;
2. Assessment of the UNF inventory relative to retention needs for RD&D, potential future recycle, and recovery for national security interests;
3. Determination of appropriate categories and criteria for categorizing the UNF inventory; and
4. Categorization of the UNF inventory relative to the identified categories.

Key tenets and assumptions include the following.

1. Access to some amount of UNF is needed to support RD&D for the DOE-NE FCT program objectives related to UNF management and alternative fuel cycles.

2. The two principal options for addressing UNF management are geologic disposal and recycling.

3. U.S. nuclear power plants will continue to discharge ~2000 MTHM annually for the next couple of decades; projections beyond the next couple of decades are less certain.

4. The option of recycling commercial UNF at a future date is maintained, pending a decision.

5. Although fuel recycling depends on future decisions, it is assumed that industrial-scale (100s to 1000s of MTHM/y) recycling of commercial UNF is unlikely to begin for at least 20 years (2030 time frame), at which time an additional ~40,000 MTHM of UNF will have been discharged.

6. Recycling in any potential future alternative fuel cycle would likely be designed and optimized for the material needs of the associated reactor fleet based on the current and projected UNF discharges and inventory at that time, rather than UNF feedstock that is no longer being produced.

7. The time frame for the development of alternative fuel cycles is assumed to be consistent with the schedule in the DOE-NE R&D Roadmap.

8. It is assumed that the transportation and placement of the current UNF inventory in disposal is unlikely to begin for at least 10 years and will take several decades.

This report is organized as follows. Relevant background information is provided in Section 1.1. An overview of the domestic UNF inventory is presented in Section 2. Section 3 provides an assessment of the UNF relative to retention needs. Section 4 defines the categories and criteria used for categorizing the UNF inventory. Section 5 presents the results of the categorization. Conclusions and suggestions for future work are described in Sections 6 and 7, respectively.

1.1 BACKGROUND

In 2010, the DOE-NE developed a research and development (R&D) roadmap[2] to ensure nuclear energy remains a viable energy option for the United States. The DOE-NE Roadmap identified the following key challenges to the increased use of nuclear energy.

- "The capital cost of new large plants is high and can challenge the ability of electric utilities to deploy new nuclear power plants.
- The exemplary safety performance of the U.S. nuclear industry over the past thirty years must be maintained by an expanding reactor fleet.
- There is currently no integrated and permanent solution to high-level nuclear waste management.
- International expansion of the use of nuclear energy raises concerns about the proliferation of nuclear weapons stemming from potential access to special nuclear materials and technologies."

To address the challenges to expanding the use of nuclear energy, the DOE-NE Roadmap organized the R&D activities along the following four main R&D objectives.

1. Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
2. Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals.
3. Develop sustainable nuclear fuel cycles.
4. Understand and minimize the risks of nuclear proliferation and terrorism.

As described in the DOE-NE Roadmap, sustainable fuel cycle options are those that improve uranium resource utilization, maximize energy generation, minimize waste generation, improve safety, and limit

proliferation risk. The key challenge identified in the DOE-NE Roadmap is to develop a suite of options that will enable future decision makers to make informed choices about how best to manage the used fuel from reactors. Hence, according to the DOE-NE Roadmap, DOE will conduct R&D in this area to investigate the technical challenges involved with the following three potential strategies for used fuel management.

- *"Once-Through* – Nuclear fuel makes a single pass through a reactor after which the used fuel is removed, stored for some period of time, and then directly disposed in a geologic repository for long-term isolation from the environment. The used fuel will not undergo any sort of treatment to alter the waste form prior to disposal in this approach, eliminating the need for separations technologies that may pose proliferation concerns. Less than one percent of the mined uranium is utilized in the present once-through fuel cycle.
- *Modified Open Cycle* – The goal of this approach is to develop fuel for use in reactors that can increase utilization of the fuel resource and reduce the quantity of actinides that would be disposed in used fuel. This strategy is "modified" in that some limited separations and fuel processing technologies are applied to the used LWR fuel to create fuels that enable the extraction of much more energy from the same mass of material and accomplish waste management goals.
- *Full Recycle* – In a full recycle strategy, all of the actinides important for waste management are recycled in thermal- or fast-spectrum systems to reduce the radiotoxicity of the waste placed in a geologic repository while more fully utilizing uranium resources. In a full recycle system, only those elements that are considered to be waste (primarily the fission products) are intended for disposal, not used fuel. Implementing this system will require extensive use of separation technologies and the likely deployment of new reactors or other systems capable of transmuting actinides."

The R&D to support future decisions is to be conducted during the next few decades to support the FCT Program Vision:[1] "By mid-century, strategies and technologies for the safe long-term management and eventual disposal of U.S. commercial UNF and any associated nuclear wastes have been fully implemented." The technical assessment described in this report is part of the FCT R&D program and is intended to support near-term and future decisions regarding fuel cycle strategies and R&D needs. Between now and mid-century, ~40 years of additional discharged commercial UNF could be accumulated, which, based on the current annual discharge rate,[*] could be as much as 80,000 MTHM of additional UNF. While in theory all 80+ years of UNF could be recycled, the practicalities, cost, and potential benefits of doing so must be properly considered. Therefore, the UNF inventory is assessed in this report to determine the type and quantity of UNF that may be needed to support the DOE-NE research objectives, including maintaining the fuel cycle strategy options described above. The focus of this assessment is on the determination of the characteristics and amounts of UNF that should be retained for potential future use and those that should be designated for permanent disposal.

[*]It is recognized that the annual discharge rate may vary considerably over the next 40 years.

2. OVERVIEW OF THE DOMESTIC USED NUCLEAR FUEL INVENTORY

The current (as of 2011) domestic UNF inventory includes UNF from commercial nuclear electricity generation and defense and research programs stored at 79 sites in 34 states. The diversity of UNF types, characteristics, storage locations, and storage conditions presents a variety of challenges to the safety, security, and cost of UNF management. The current mass of fuel in each of the categories is shown in Figure 1. The inventory of discharged commercial UNF is currently ~67,600 MTHM[3] and is increasing by ~2000 MTHM annually.[4] The inventory of DOE-owned UNF is currently ~2500 MTHM and is not increasing at an appreciable annual rate. The inventory of HEU is currently ~50 MTHM. Additional details on these UNF inventory constituents are provided in the following subsections.

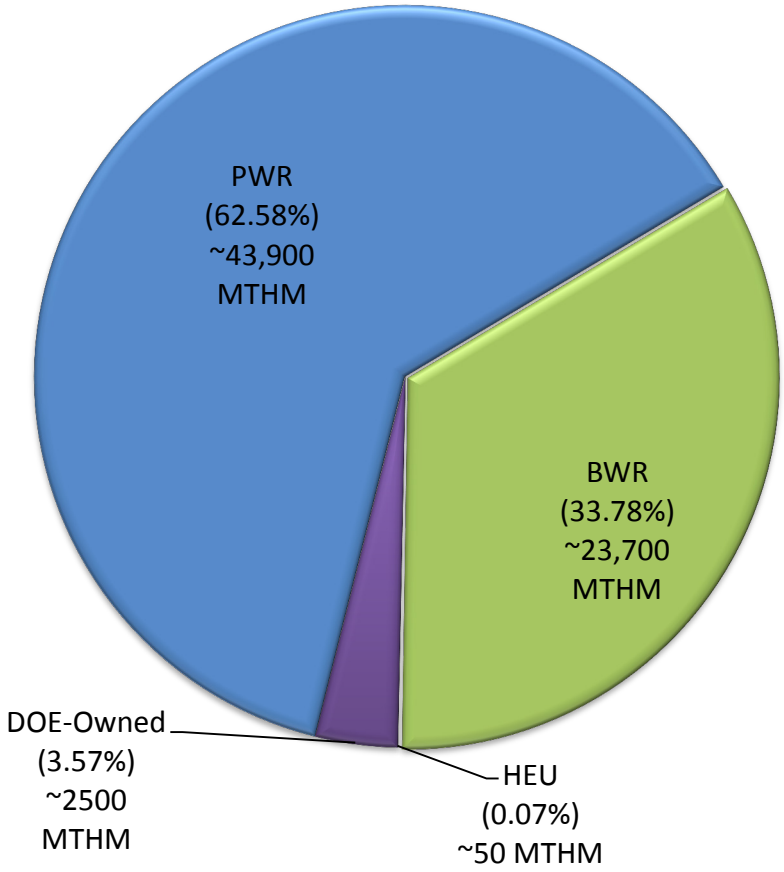

Figure 1. Mass of UNF inventory constituents as of 2011 (HEU portion too small to be visible). *Source*: Ref. 3.

2.1 COMMERCIAL USED NUCLEAR FUEL

Approximately 67,600 MTHM of commercial UNF, representing a total of ~23 billion curies of long-lived radioactivity,[3] are currently stored at 75 sites in 33 states.[4] The commercial UNF inventory is currently increasing annually by ~2,000 MTHM[4] and will increase at a greater rate in the future if the number of operating nuclear reactors increases. Commercial UNF discharge data, on an assembly basis, were collected and published[5] by the Energy Information Administration for the Office of Civilian

Radioactive Waste Management through 2002. Although limited to discharges through 2002, these data represent the most detailed available information on the commercially discharged UNF inventory. More recently, data have been assembled from a variety of sources by the DOE-NE Used Fuel Disposition Campaign (UFDC) to develop an inventory estimate through 2011.[3] Data from both of these sources were used in this assessment.

Commercial nuclear power plants have been operating in the United States since 1957,[*] and there are currently 104 operating nuclear power plants. Used nuclear fuel from these plants is stored on-site in spent fuel pools and in dry storage casks, complicating the cost and issues associated with UNF management. Dry storage facilities, referred to as independent spent fuel storage installations (ISFSI), are in operation at the majority of reactor sites, including 10 sites in 9 states that no longer have operating reactors. Figure 2 shows the location of operating and shutdown commercial reactor sites. Commercial UNF includes irradiated fuel discharged from pressurized water reactors (PWRs) and boiling water reactors (BWRs). In 2011, ~74% of the total mass of commercial UNF was stored in spent fuel pools, and the remaining 26% was in dry cask storage.[6] However, these proportions will slowly change[6,7] as most spent fuel pools are at or near their capacity. The distribution of the current UNF inventory from PWRs and BWRs in wet (pool) and dry storage is illustrated in Figure 3.

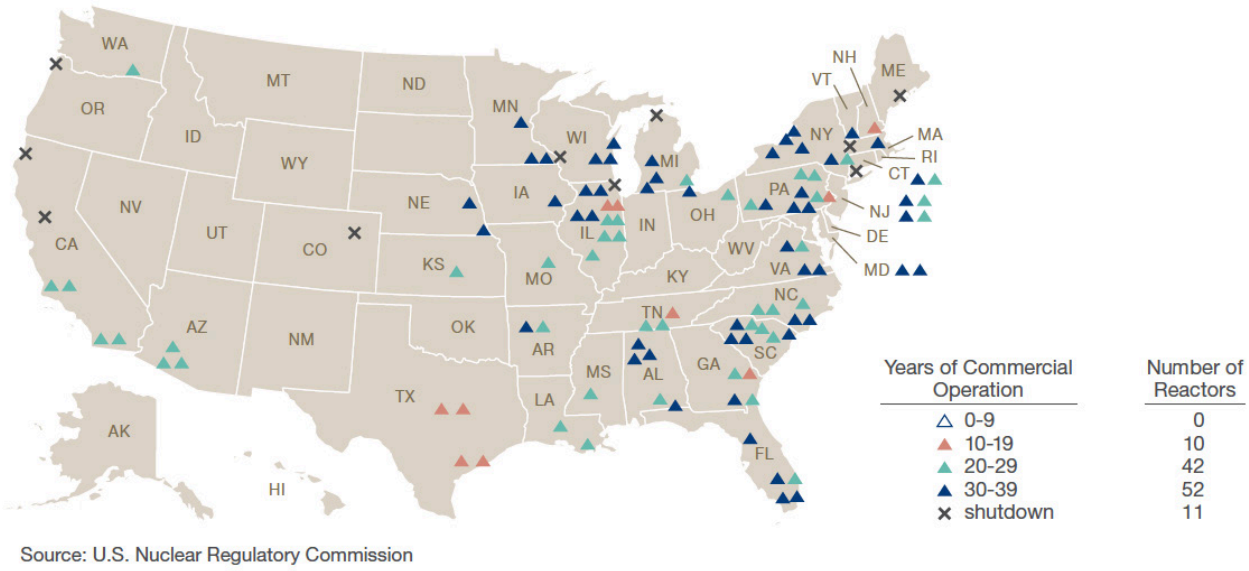

Figure 2. Operating and shutdown commercial reactor sites.

[*]Note that the UNF from the first commercial nuclear power plant, the Shippingport Atomic Power Station, is now classified as DOE-owned fuel.

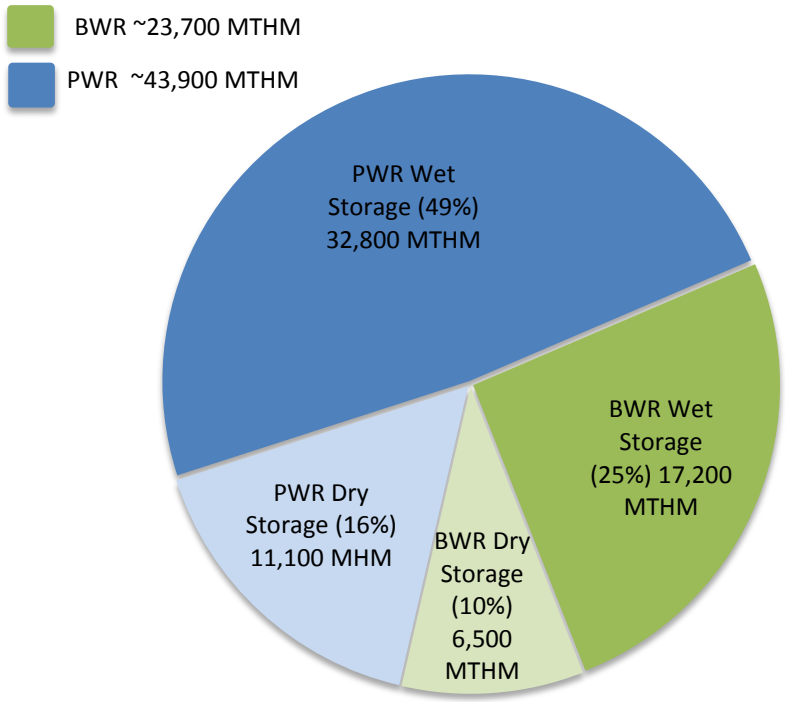

Figure 3. Distribution of current (2011) commercial UNF inventory from PWRs and BWRs in wet and dry storage (data from Refs. 3, 5, 6, and 8).

The fuel used in commercial nuclear power reactors consists of uranium dioxide pellets encased in zirconium alloy (Zircaloy) tubes for the majority of the fuel and in stainless steel tubes for a much smaller fraction. The fuel assemblies vary in physical configuration, depending on reactor type and manufacturer, and have evolved in the United States over the past several decades. BWRs have used fuel assemblies arranged in 6×6, 7×7, 8×8, 9×9, 10×10, and 11×11 arrays of fuel pins, as well as some nonsymmetric configurations and a range of lattice variations, such as water holes and part-length rods. PWRs have used fuel assemblies arranged in 14×14, 15×15, 16×16 and 17×17 arrays of fuel pins. The distributions of assembly lattice sizes and fuel vendors for the current inventory of discharged UNF are shown in Figures 4 and 5, respectively. The different reactor types and evolution in fuel assembly designs and reactor operating conditions have resulted in considerable variation in the characteristics (e.g., assembly and cladding materials, initial enrichment, discharge burnup, burnable poison types, and irradiation exposure conditions) of the current UNF inventory. The variation is evident in the fact that commercial UNF assemblies have been categorized[5] by physical configuration into 22 classes: 16 PWR and 6 BWR fuel assembly classes. In Appendix A, Tables A-1 and A-2 present the assembly class, array size, fuel manufacturer, assembly version, assembly type code, length, width, and cladding material of commercial PWR UNF and commercial BWR UNF, respectively. Within an assembly class, assembly types are of a similar size. There are 137 individual fuel assembly types in these 22 classes. Table A-3 presents the number of assemblies, initial uranium load, enrichment, burnup, and cooling time characteristics of the commercial PWR and BWR UNF assembly types, respectively. Tables A-4 and A-5 provide summaries of UNF characteristics from samples, PWR fuel assemblies, and BWR fuel assemblies. The significant variation in the current inventory is illustrated in Figure 6 , which shows the distribution of the 22 assembly classes, and Figure 7 and Figure 8, which show the distribution of the fuel assembly types for PWRs and BWRs, respectively. Although Figure 7 and Figure 8 are somewhat difficult to decipher, they

illustrate the extent of the variation in assembly types within the domestic commercial discharged UNF inventory. These variations raise issues with aspects of commercial UNF management (e.g., demonstrating compliance with storage, transportation, and disposal regulatory criteria for all the variations present in the current UNF inventory) and the viability of recycling (e.g., designing and operating a recycling facility and associated processes that can accommodate such wide variations in feedstock).

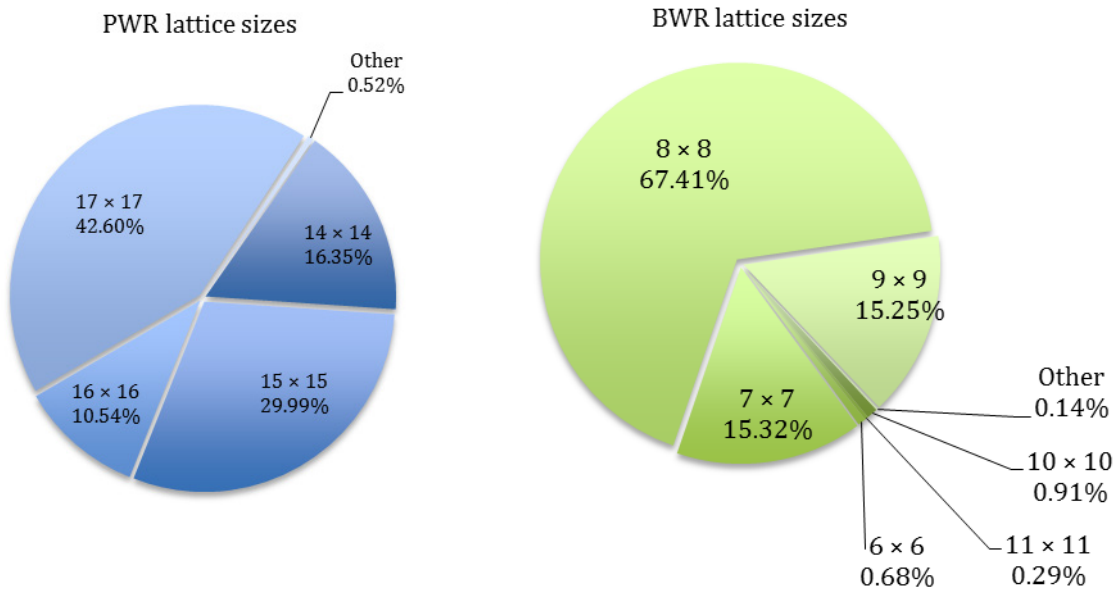

Figure 4. Distribution (through 2002) of assembly lattice sizes by mass (units are percentage of total MTHM) in the commercial UNF inventory. *Source*: Ref. 5.

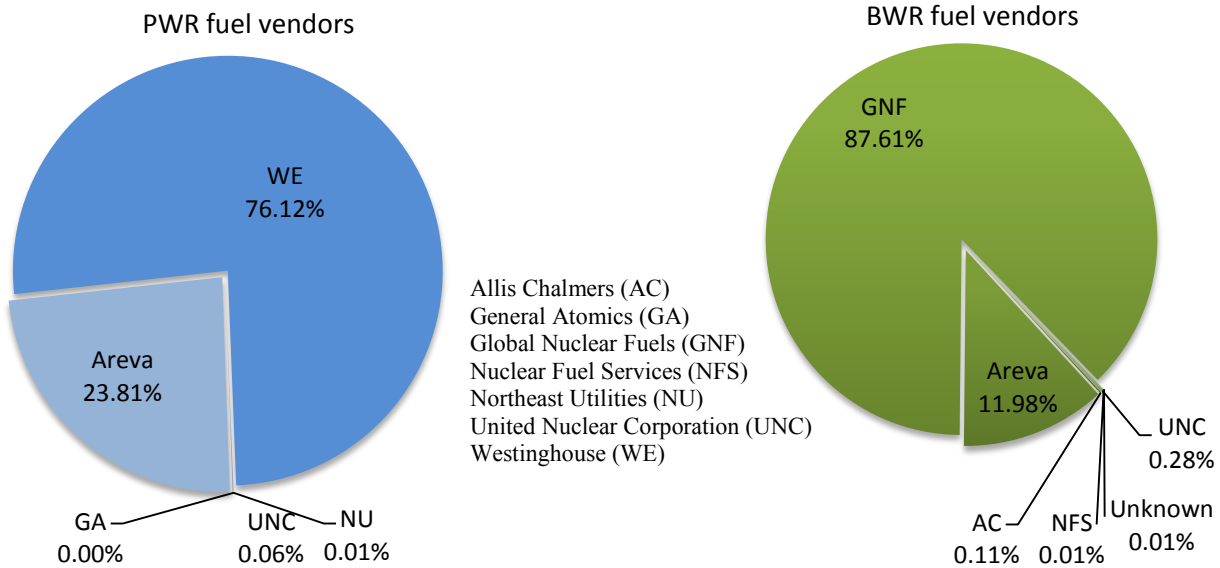

Figure 5. Distribution (through 2002) of fuel vendors by mass (units are percentage of total MTHM) in the commercial UNF inventory. *Source*: Ref. 5.

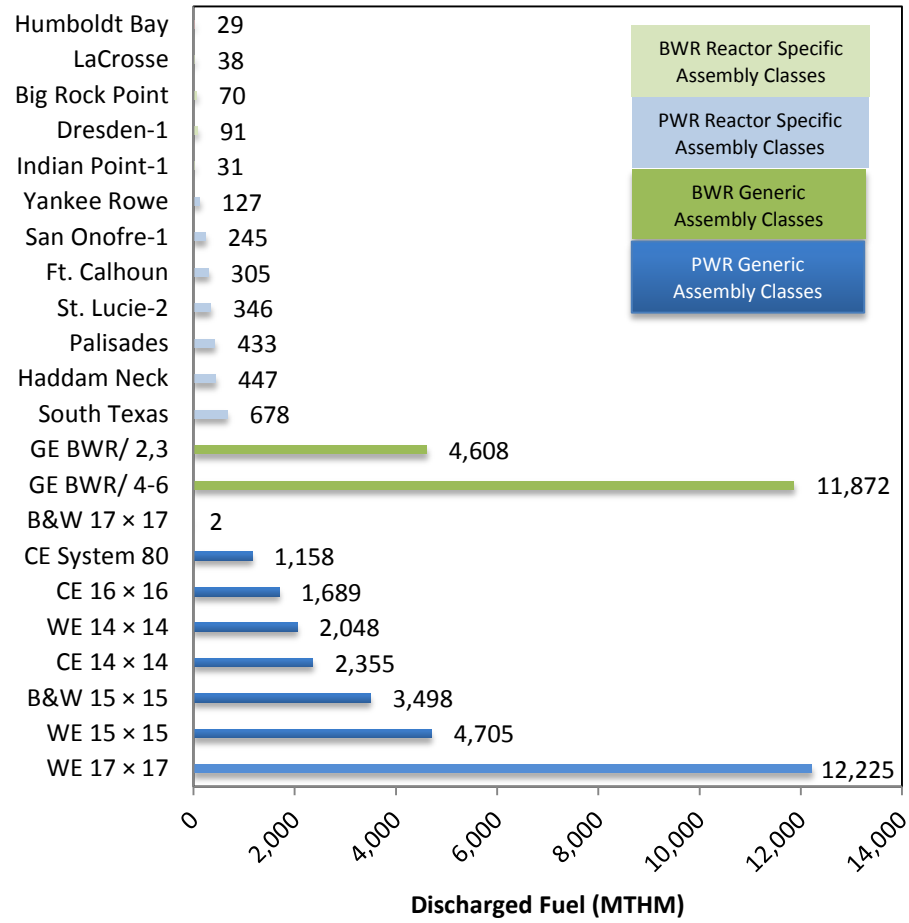

Figure 6. Distribution of assembly classes by total mass in the commercial UNF inventory as of 2002. *Source*: Ref. 5.

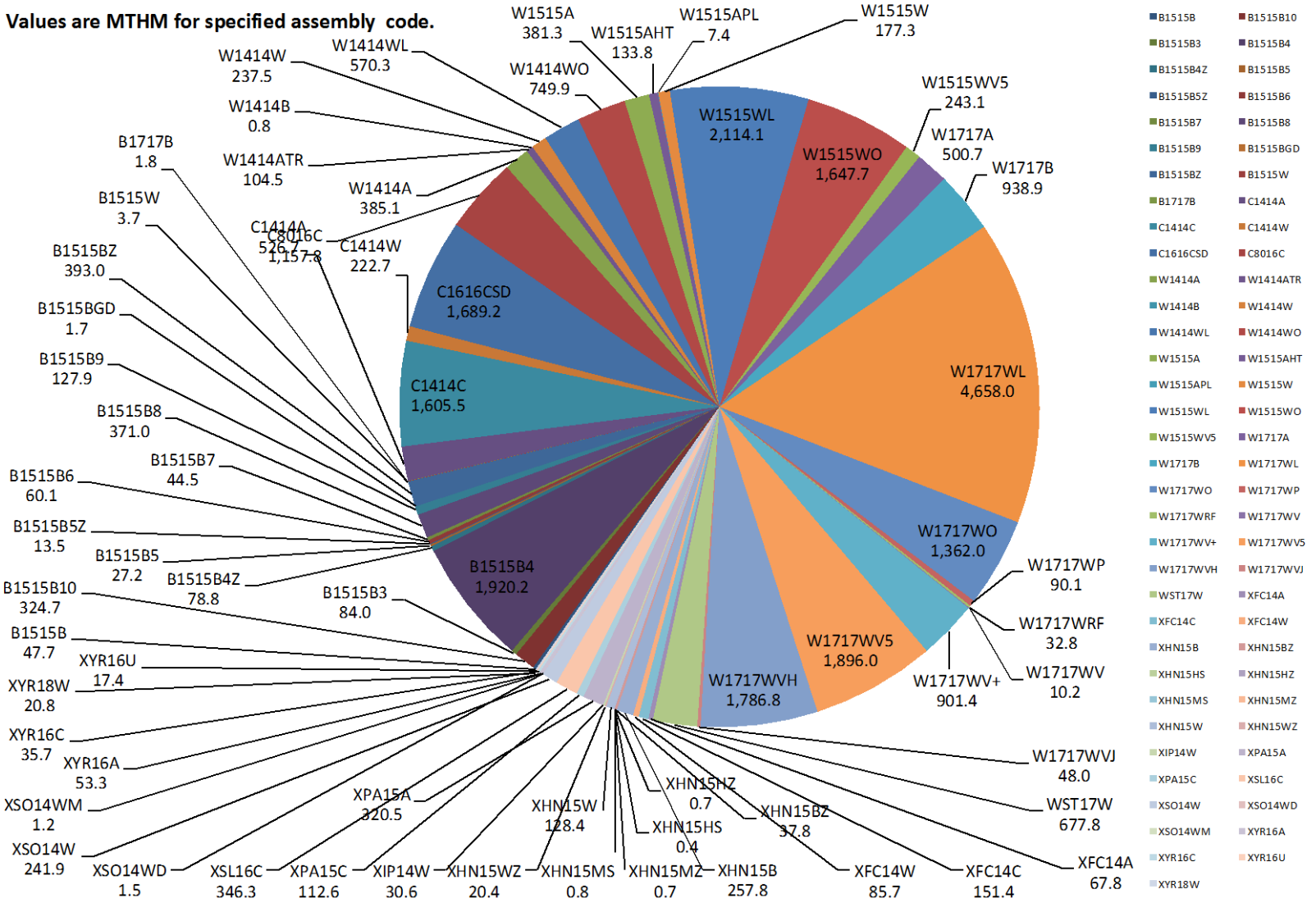

Figure 7. Distribution of PWR fuel assembly types by mass (units of MTHM) in the commercial UNF inventory as of 2002. *Source*: Ref. 5.

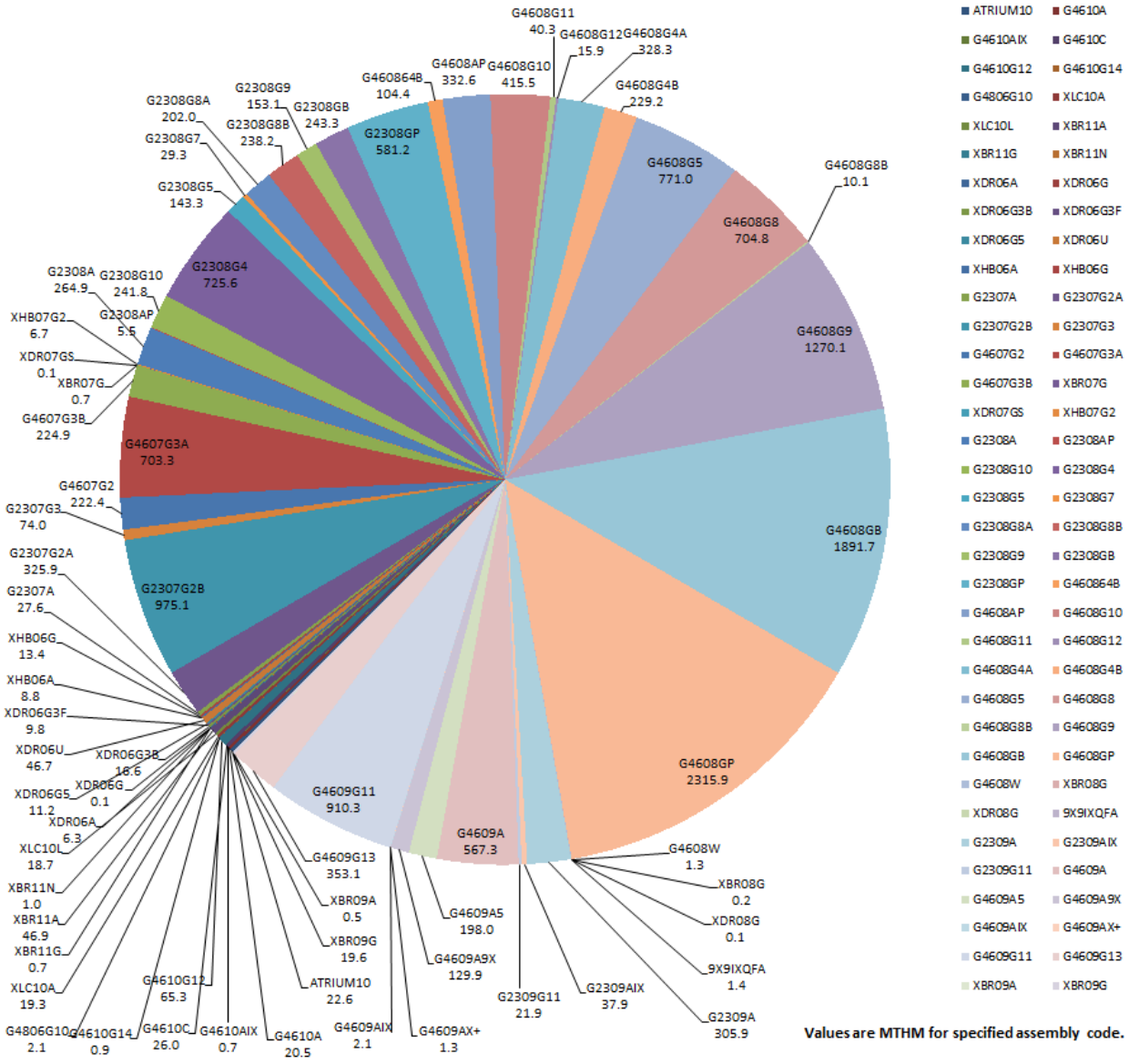

Figure 8. Distribution of BWR fuel assembly types by mass (units of MTHM) in the commercial UNF inventory as of 2002. *Source*: Ref. 5.

The significant variation in the discharged UNF inventory reflects the evolution of nuclear reactor and fuel assembly designs during the first ~50 years of nuclear power operation. Examination of discharges in recent years indicates that the variability in discharged fuel assemblies has decreased with time. For example, Figure 9 shows how assembly-average enrichment has increased across the U.S. commercial reactor fleet and is approaching the current limit of 5 wt % ^{235}U, and Figure 10 shows how burnup values have been increasing and will ultimately be limited by the limit on initial fuel enrichments.[*] Figures 11 and 12 plot PWR and BWR, respectively, assembly class discharges as a function of time and show

[*]Note that if the current commercial reactor-licensing limit of 5.0 wt % ^{235}U on fuel enrichment was increased in the future, fuel design variations would be implemented to utilize higher enrichments and discharge burnup values would increase.

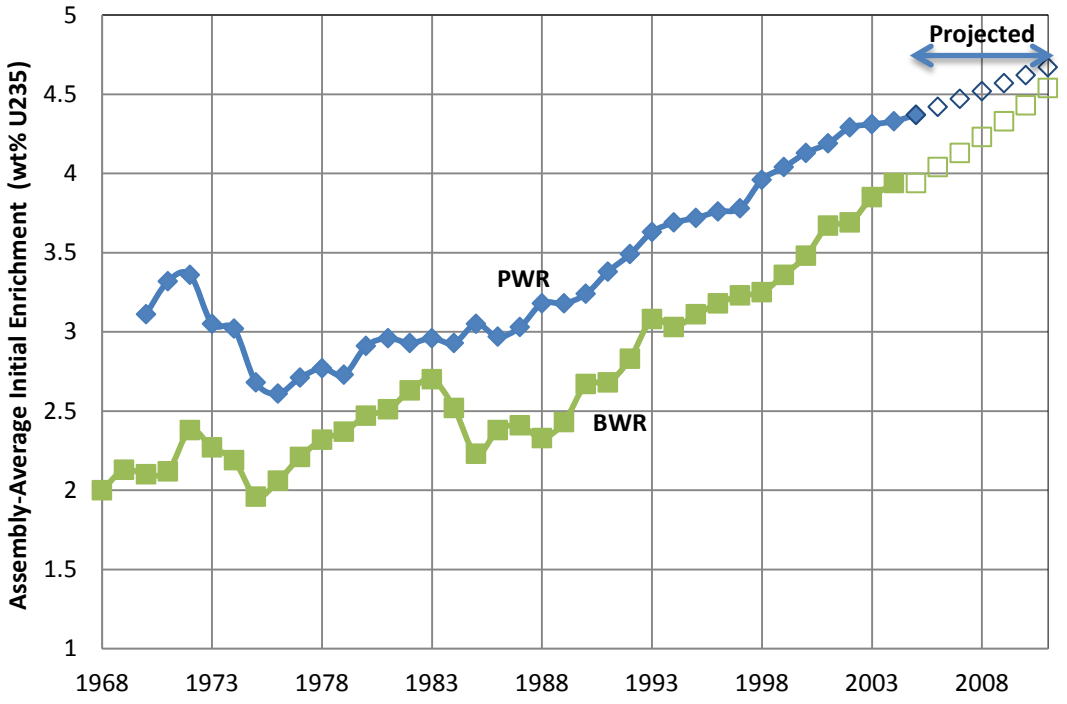

Figure 9. Assembly-average initial enrichment as a function of time. *Source*: Ref. 3.

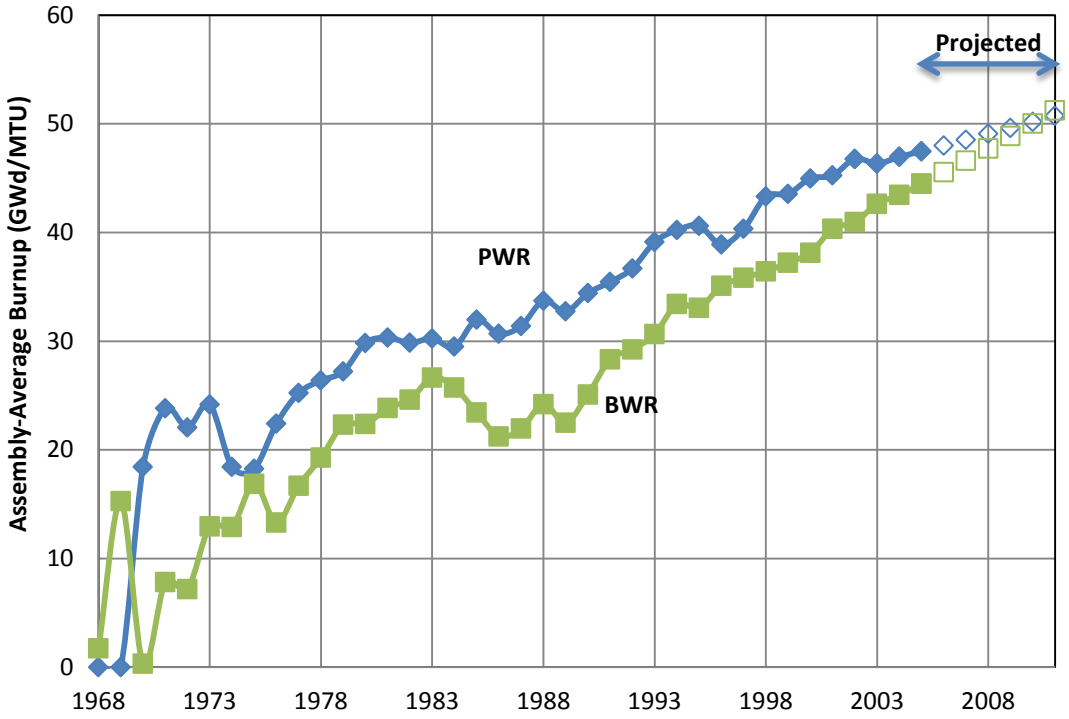

Figure 10. Assembly-average discharge burnup as a function of time. *Source*: Ref. 3.

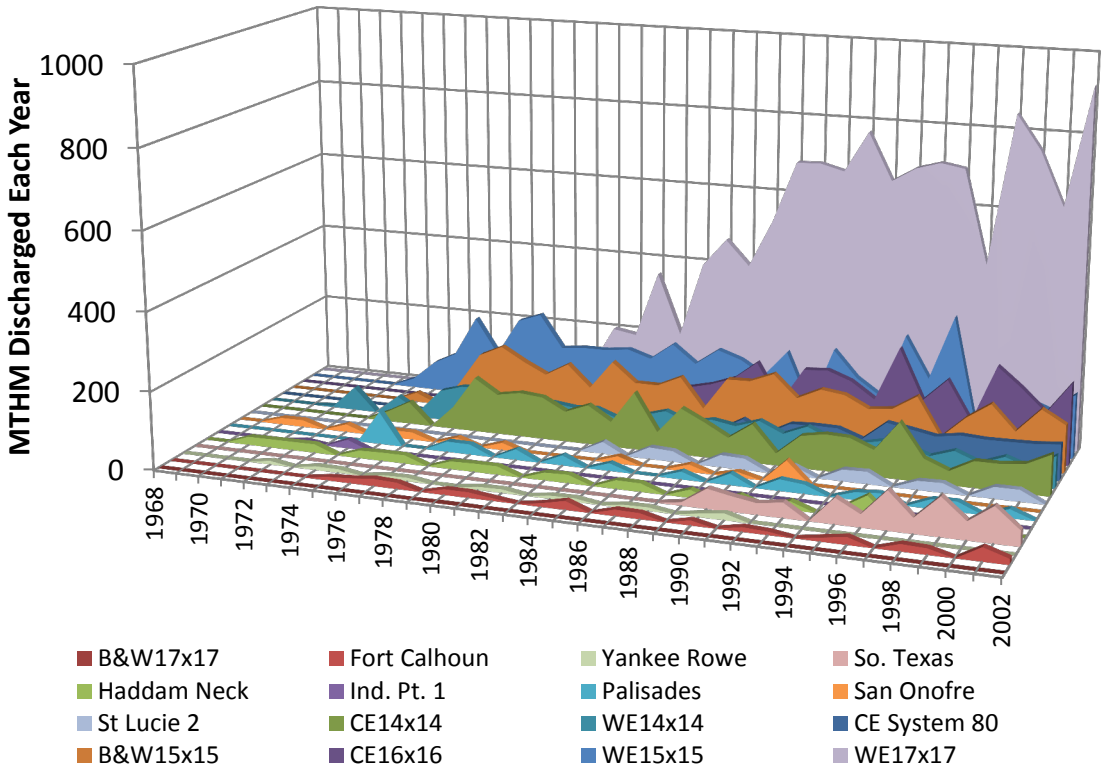

Figure 11. PWR assembly class discharges as a function of time through 2002. *Source*: Ref. 5.

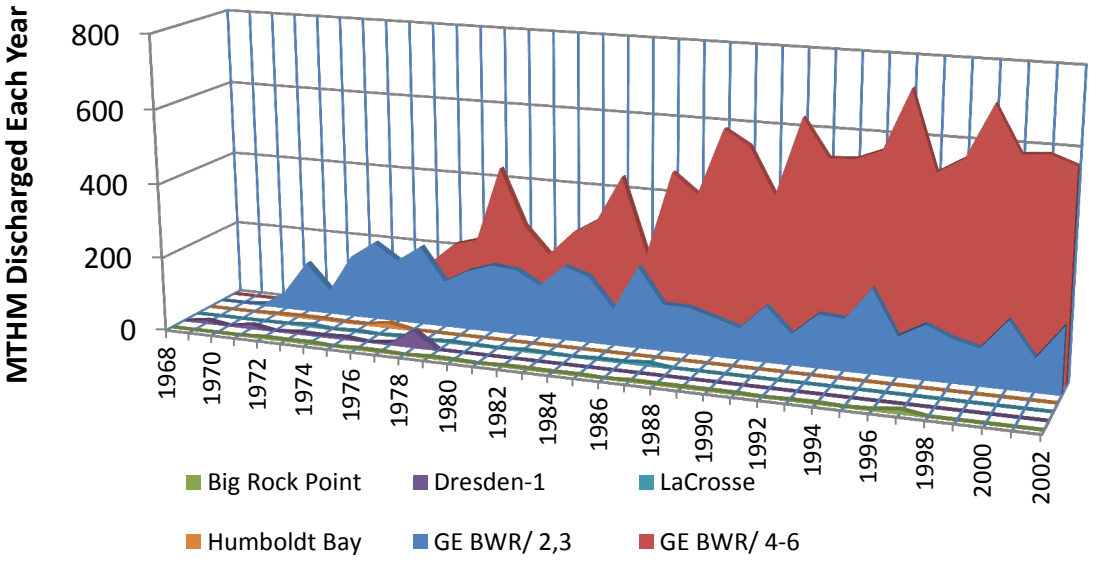

Figure 12. BWR assembly class discharges as a function of time through 2002. *Source*: Ref. 5.

how the variation in assembly classes is decreasing as a number of fuel types, particularly reactor-specific fuel types, have been discontinued. Looking forward, less variation in fuel assembly designs is expected as designs have approached the current limit of 5 wt % ^{235}U for initial enrichment, discharge burnup values are more uniform as they approach their upper limits, and many of the reactor-specific assembly designs are no longer being used. Also, a review of new PWR reactor designs for which combined (construct and operate) license (COL) applications have been submitted,[9] that is, AP1000, U.S. EPR, and U.S. APWR, indicates that all of these reactor designs will use fuel with the same assembly lattice size (i.e., 17×17). This provides further support for the expectation that UNF discharges in future decades will likely have more uniform characteristics than past or current UNF discharges.

In summary, the current (as of 2011) inventory of domestic commercial UNF is massive (~67,600 MTHM), diverse (22 unique assembly classes with varying physical characteristics and dimensions), dispersed (stored at 75 sites in 33 states in a variety of wet and dry storage systems), increasing (increasing by ~2000 MTHM/y), and evolving (reactor-specific assembly designs being phased out, initial enrichment and discharge burnup values becoming more uniform). The diversity of UNF types, characteristics, storage locations, and storage conditions of the current UNF inventory presents a variety of challenges to the safety, security, and cost of UNF management, including disposition options.

2.2 DOE USED NUCLEAR FUEL

Over the past half-century, since the inception of nuclear reactors, the DOE and its predecessor agencies operated or sponsored a variety of research, test, training, and other experimental reactors with different characteristics from the commercial power reactors of today. There are currently several hundred distinct types of DOE-owned UNF totaling ~2500 MTHM, originating from a wide range of reactor types (such as light- and heavy-water-moderated reactors, graphite-moderated reactors, and liquid-metal-cooled fast reactors), with various cladding materials (i.e., aluminum, zirconium, stainless steel) and enrichments (varying from depleted uranium to over 93 wt % enriched ^{235}U). Many of these reactors, now decommissioned, had unique design features, such as core configuration, fuel element and assembly geometry, moderator and coolant materials, operational characteristics, and neutron spatial and spectral properties. In addition, there is a relatively large number (over 200,000) of fuel pieces or assemblies, which range from a large number of pieces for some reactors (N-Reactor, ~2100 MTHM) to a few individual pieces for other unique reactors (e.g., Chicago Pile-5 converter cylinders).

DOE-owned UNF generated in production reactors supported weapons and other isotope production programs. An example of UNF from production reactors is the N-reactor UNF stored at the Hanford, Washington site. Some UNF from commercial power reactors (such as Shippingport, Peach Bottom, Fort St. Vrain, Turkey Point, and Surry) is also stored within the DOE complex. This UNF was generated for commercial power demonstration purposes or obtained as part of research projects. In addition, the Three Mile Island Unit 2 UNF debris is stored at the Idaho National Laboratory (INL) and commercial UNF obtained for research purposes is stored in different locations across the DOE national laboratory complex. DOE has also sponsored nuclear research activities overseas. Research reactor UNF is being returned to the United States from foreign research reactors as part of the DOE Foreign Research Reactor Spent Nuclear Fuel Acceptance Program.[10]

Recent data on the DOE-owned UNF were collected and published by the DOE-NE UFDC.[3] The majority of the DOE-owned UNF (~2500 MTHM) is already in storage, with around 2100 MTHM contained in about 400 sealed canisters.[3] The only new DOE-owned UNF comes from the operation of several research reactors, from university research reactors, and from the Foreign Research Reactor Spent Nuclear Fuel Acceptance Program. The predicted DOE-owned UNF inventory to be discharged from these three sources is relatively small (about 50 MTHM).[3]

To support analyses, the DOE-owned UNF inventory has been divided into 34 DOE UNF groups based on fuel matrix, cladding, cladding condition, and enrichment. A discussion of each of the 34 groupings is presented elsewhere,[3] and Table B-1 in Appendix B describes the typical ranges of the nominal properties for DOE UNF in the 34 groups.

2.3 HIGHLY ENRICHED URANIUM USED NUCLEAR FUEL

Highly enriched uranium UNF has been generated from a variety of reactors supporting research and defense programs,. Approximately 50 MTHM of HEU UNF currently exists with an enrichment greater than 90 wt % ^{235}U .[3,11] Due to the high uranium enrichment, very small amounts of transuranic isotopes are present in the HEU UNF, as compared to commercial UNF.

3. ASSESSMENT OF USED NUCLEAR FUEL RELATIVE TO RETENTION NEEDS

Execution of the DOE-NE's Office of FCT mission to "develop used nuclear fuel management strategies and technologies to support meeting federal government responsibility to manage and dispose of the nation's commercial used nuclear fuel and high-level waste; develop sustainable fuel cycle technologies and options that improve resource utilization and energy generation, and reduce waste generation, enhance safety, and limit proliferation risk" requires immediate and continued access to select UNF material to support the following program objectives.[1]

- Develop a strengthened technical and scientific basis for extended UNF storage.
- Select preferred sustainable fuel cycle options for further development.
- Conduct science-based, engineering-driven research for selected sustainable fuel cycle options.
- Develop the scientific basis for multiple disposal options for UNF and high-level waste.
- Have implemented acceptable and safe options, strategies, and solutions for management (including extended storage and long-term disposal) of UNF and nuclear waste.
- Test and make available advanced technologies that enable sustainable fuel cycles.

All of these program objectives pertain to either UNF management or alternative fuel cycles, and hence the potential needs for access to UNF material are discussed in terms of those two categories in this section.

3.1 TENETS AND ASSUMPTIONS

The following tenets and assumptions were used in this assessment.

3.1.1 Tenets

1. Access to some amount of UNF is needed to support RD&D for the DOE-NE FCT program objectives related to UNF management and alternative fuel cycles.

2. The two principal options for addressing UNF management are geologic disposal and recycling.

3.1.2 Assumptions

1. *U.S. nuclear power plants will continue to discharge ~2000 MTHM annually for the next couple of decades*; projections beyond the next couple of decades are less certain. Annual discharge mass can be expected to decrease slightly with increasing discharge burnup values (i.e., greater energy produced per assembly). The discharge rate is most sensitive to the number of operating nuclear power plants, that is, an increase (decrease) in nuclear power utilization in the United States will increase (decrease) the annual discharge rate.

2. *The option of recycling commercial UNF at a future date is maintained*, pending a decision.

3. Although fuel recycling depends on future decisions, it is assumed that *industrial-scale (100s to 1000s of MTHM/y) recycling of commercial UNF is unlikely to begin for at least 20 years (2030 time frame)*, at which time an additional ~40,000 MTHM of UNF will have been discharged.

4. *Recycling in any potential future alternative fuel cycle would likely be designed and optimized for the material needs of the associated reactor fleet based on the current and projected UNF discharges and inventory at that time,* rather than UNF feedstock that is no longer being

produced. Since current trends indicate that future UNF will have more uniformity and high-burnup values relative to the majority of discharged UNF in the current inventory, it is assumed in the current evaluation that any potential future recycling facilities would be designed and optimized for those "standard" conditions rather than having the capability to process potentially significantly different legacy UNF. It is, however, assumed that access to a representative sample of the current inventory should be maintained for RD&D purposes, to ensure that they can be stored for an extended period, handled safely during transportation, and be safely disposed of in a repository.

5. *The time frame for the development of alternative fuel cycles is assumed to be consistent with the schedule in the DOE-NE R&D Roadmap.* Based on this assumption, reasonable projections for electricity growth, share of nuclear electricity, and the current and historical rate of deployment of new and unproven (at the industrial scale) nuclear technologies in the regulated nuclear industry, the current and projected future inventory of commercial discharged UNF is determined to exceed the material needs for any realistically conceivable future alternative fuel cycles. In other words, the material needs of future advanced reactors can be met without reliance on the current UNF inventory. It is recognized that this determination may not be valid under some scenarios that involve rapid deployment of numerous advanced reactors; however, such a rapid development is not consistent with the schedule in the DOE-NE R&D Roadmap.

6. *It is assumed that the transportation and placement of the current UNF inventory in disposal is unlikely to begin for at least 10 years and will take several decades*.[6] Hence, it is assumed that even if the nation were to proceed with disposal immediately, a large fraction of the UNF inventory will be accessible for several decades.

3.2 USED NUCLEAR FUEL MANAGEMENT

3.2.1 Used Nuclear Fuel Material Need

The domestic UNF inventory has been and continues to be managed safely. Maintaining a strong technical basis for safe and secure storage, transportation, and disposal of UNF is essential for the sustainability of nuclear power generation in the United States. At present, the long-term nuclear waste management strategy for the United States is uncertain, but the DOE is responsible for the ultimate disposition of the UNF. The DOE-NE FCT established the UFDC to provide technical support for this responsibility. The UFDC is chartered to identify alternatives and conduct scientific research and technology development to effectively manage (i.e., store, transportation, and dispose) UNF and waste generated by existing and alternative nuclear fuel cycles. In support of this charter, the UFDC completed a technical gap analysis for extended storage[12] in January 2012 and for transportation[13] in August 2011. Both efforts, as well as similar efforts by the Nuclear Regulatory Commission (NRC),[14] the Electric Power Research Institute (EPRI),[15] and the Nuclear Waste Technical Review Board (NWTRB),[16] identified data and modeling needs and proposed RD&D activities for each gap. Although the details have yet to be finalized, RD&D plans are being developed to support closure of these technical gaps and access to a representative sample, as well as sufficient quantities to enable reliable statistical analyses, of the diverse commercial UNF inventory is an identified need to support phenomenological/separate effects, small-scale, and full-scale demonstration testing.[17] Therefore, it is considered prudent to retain access to a sufficient quantity of representative samples of commercial UNF to support planned RD&D efforts and to be available to support addressing questions and issues that may arise in the future. Although the focus of this report is on UNF, it is noted that RD&D needs to support storage, transportation, disposal, and potential recycling of non-fuel components, such as rod control cluster assemblies (RCCAs), axial power shaping rod assemblies (APSRAs), burnable poison rod assemblies (BPRAs), and control blades. Such components should also be considered and addressed.

3.2.2 Selection Criteria for Used Nuclear Fuel

As discussed in Section 2.1, the current U.S. commercial UNF inventory includes a wide variety of fuel assembly designs by several reactor vendors that have experienced varying reactor operating and storage histories. Given that there is a recognized need to maintain access to a sufficient quantity of representative samples of commercial UNF to support UNF management, the next step is to determine the important characteristics of those representative samples and estimate the needed quantities to support identification of material for retention. With this objective in mind, a review of the U.S. UNF inventory and previous similar efforts[18] was performed with the intent of identifying criteria for selecting representative samples and sufficient quantities for retention of access. Some of the selection criteria are focused on specific issues such as understanding and predicting clad integrity and those affecting fuel assembly long-term structural integrity, while others are focused on ensuring access is maintained to UNF representing the full range of parameters characterizing the UNF inventory to support resolution of potential future issues. At this point, it was decided to err on the side of inclusion, such that future refinements of the selection criteria might reduce the variety and amount of material for which access is retained. Furthermore, at this stage, no attempt has been made to identify individual fuel assemblies for retention. The following sections describe the selection criteria used in this assessment, which can be grouped into the following two main categories: (1) assembly design and (2) assembly exposure and operating history.

3.2.2.1 Assembly Design (Lattice and Materials)

Commercial nuclear power plants have been generating UNF since the first commercial nuclear power plant began operation in 1957. As of the end of 2011, an estimated 234,000 fuel assemblies containing 67,600 MTHM were identified as discharged.[3] BWRs have used fuel assemblies arranged in 6×6, 7×7, 8×8, 9×9, 10×10 and 11×11 arrays of fuel pins. PWRs have used fuel assemblies arranged in 14×14, 15×15, 16×16 and 17×17 arrays of fuel pins. There have been many variations within each assembly array (or lattice) size such that Ref. 5 identified 137 distinct BWR and PWR fuel assembly types. Since 2002, additional fuel types have been introduced. Design variations include fuel pellet diameter variations, number, size, and placement of water rods in BWR assemblies, fuel rod clad material, fuel guide tube material, grid strap material, and many other variations. There have also been relevant variations within many of the fuel assembly types. For example, the use of integral or "built-in" burnable absorbers, such as Gd_2O_3 mixed in the fuel pellet and ZrB_2 coated on the surface of fuel pellets, may affect the long-term properties of the fuel material.

Because many of the aforementioned design variations are directly relevant to the performance of the UNF assemblies during extended storage, transportation, and disposal, one of the more important selection criteria is to retain representative samples and sufficient quantities of each major lattice manufactured by each of the vendors, including variations in fuel rod clad, grid, and assembly hardware materials used. Consideration should be given to including UNF with the various integral fuel burnable absorbers and with axial blankets. Although the various UNF storage, transportation, and disposal RD&D plans are not yet completed, it is expected that much of the needed RD&D can be performed on representative fuel rods, as opposed to full fuel assemblies.

3.2.2.2 Assembly Exposure and Operating History

Assembly Burnup. As all phenomena relevant to UNF storage, transportation, and disposal are directly or indirectly related to fuel burnup, fuel samples should be selected to cover the full range of burnup values. Of particular interest are assemblies with high burnup, as concerns have been raised relative to cladding integrity of high-burnup fuel.[19] Such assemblies have received the highest integrated radiation doses and thermal stresses, and may have cladding walls with reduced thickness from in-reactor

formation of oxides or zirconium hydride. Assemblies representing the full range of assembly burnup values are also of interest to support development of burnup-dependent models for fuel degradation mechanisms and validation of a variety of computational predictions.

Figure 13 shows the distribution of assembly average burnup values as of the end of 2002, and Figure 10 shows how assembly average discharge burnup values have increased with time. It is recommended that access be retained to fuel assemblies with burnup values throughout the range of 10 to 60 GWd/MTU.

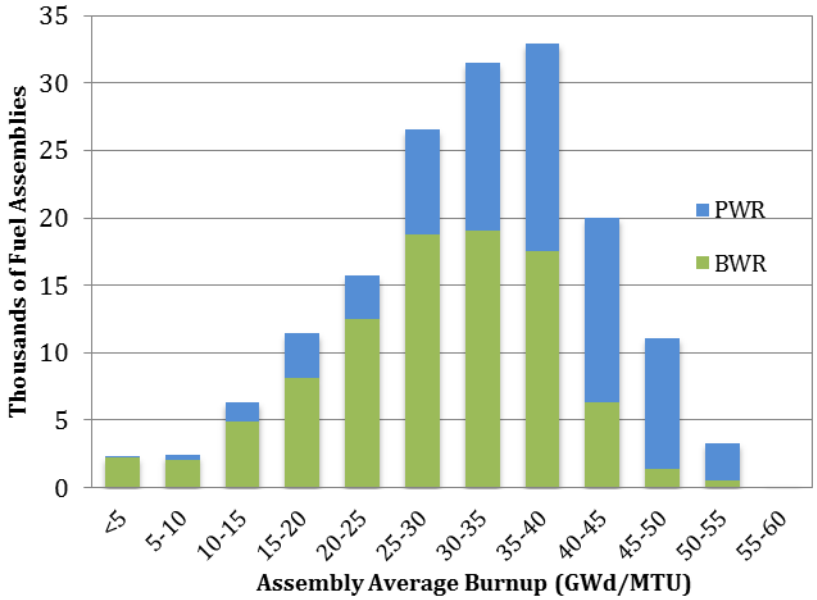

Figure 13. Distribution of assembly average burnup for all PWR and BWR fuel assemblies discharged through 2002. *Source*: Ref. 5.

Cooling time (time after discharge from the reactor). Some of the UNF currently in the commercial inventory has been stored for more than 40 years, and a portion (~10%) has been stored for 30 years or more. To the extent practicable, UNF with cooling times out to 40 years should be included in the UNF retained for future study. The availability of a continuum of cooling times could support studies of UNF aging. Figure 14 provides a characterization of the cooling time experienced by UNF as of 2011. From this figure, ~16% of the UNF was discharged less than 5 years ago.

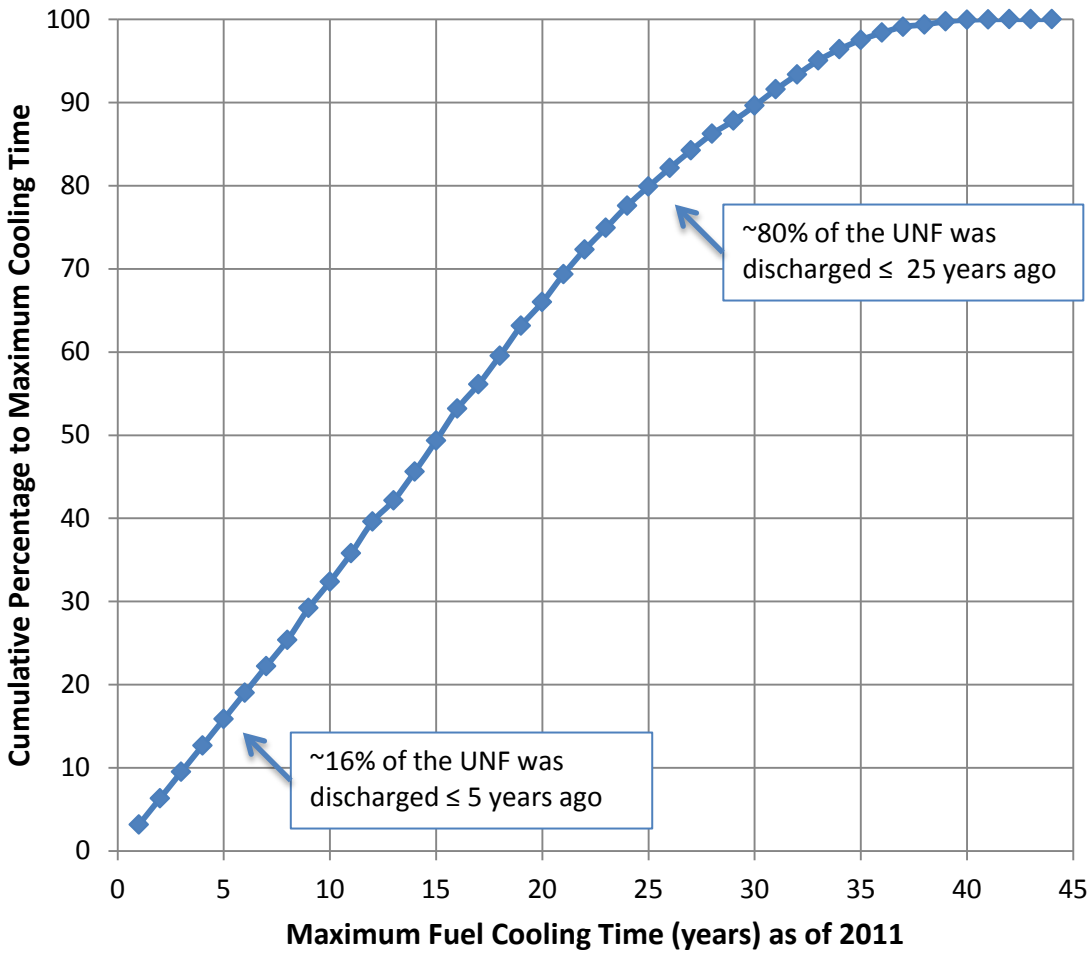

Figure 14. Post-irradiation cooling time as of 2011 (data through 2002 from Ref. 5; annual discharge of 2000 MTHM assumed after 2002).

Reactor Environment. The conditions under which the fuel is used vary from reactor to reactor and cycle to cycle and can directly impact fuel performance during and following irradiation. Selection of UNF should include consideration of the variation in coolant chemistry, shutdown periods between operating cycles, exposure to removable absorbers such as RCCAs, APSRAs and BPRAs, and the reactor average power density.

Post-Irradiation Storage Environment. As of 2011, ~26% (by mass) of UNF has been placed in dry cask storage.[6] The remainder (~74%) is stored (wet) in spent fuel pools. Some of the dry storage casks were loaded more than 15 years ago (Figure 15). Retained UNF should include samples of UNF that have been in dry and wet storage conditions for varying amounts of time to support study of the impacts of long-term storage, including investigations of cladding integrity and assembly material corrosion.

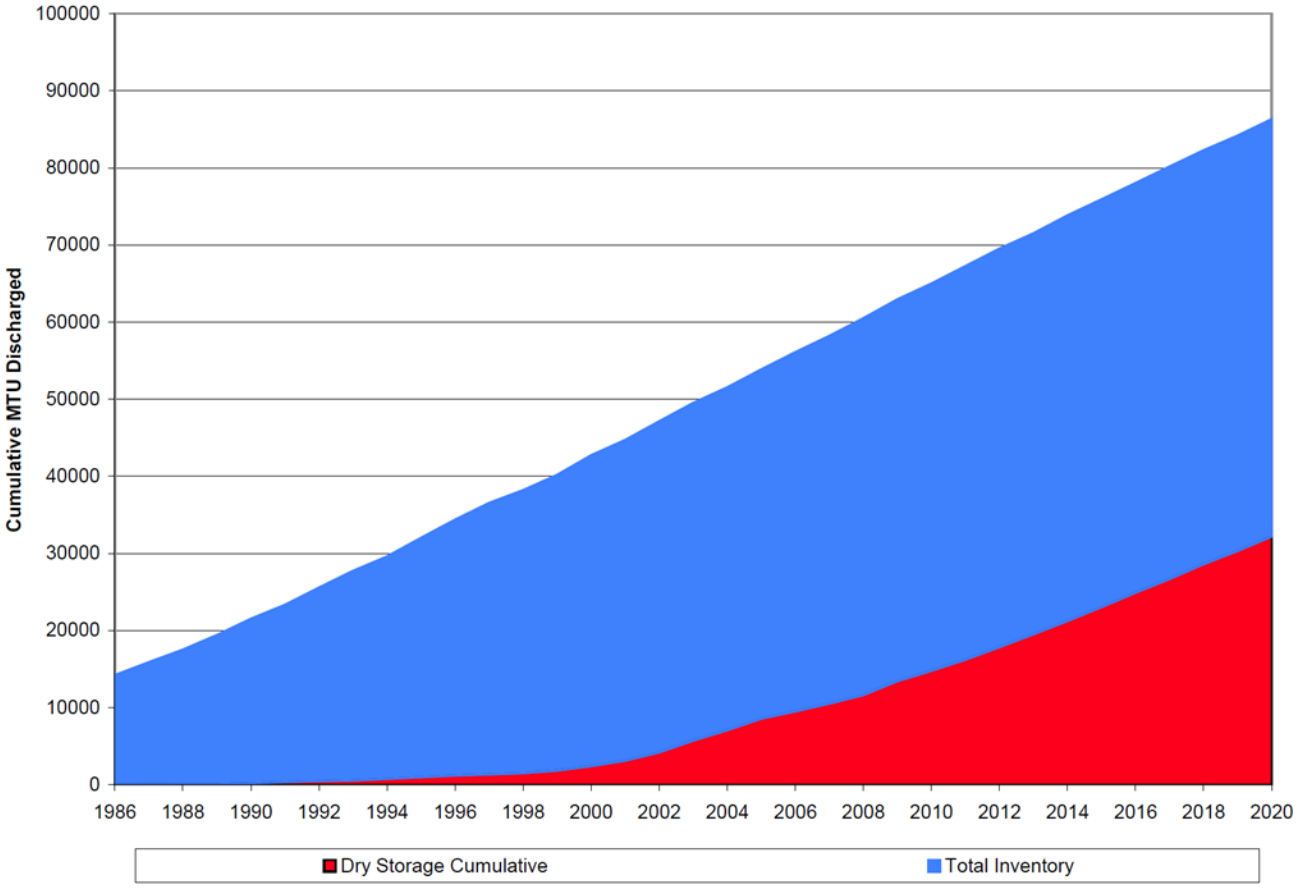

Figure 15. Historical and projected discharges of commercial used nuclear fuel. *Source*: Ref. 7.

For UNF that is currently in dry storage, a variety of dry storage cask systems have been used throughout the U.S. Selection of UNF for retention of access could include consideration of cask designs used and the environment in which the cask systems have been used. Factors considered might include above ground versus below ground storage and local climate variation, such as exposure to marine environments. Retention of a variety of cask designs would prove useful for studying the long-term integrity of various dry storage systems, including canister integrity, and is consistent with proposed full-scale demonstration testing to support industry-wide aging management plans. For UNF that is currently in wet storage, selection of UNF for retained access should consider variation in the spent fuel pool environment, such as water chemistry.

Post-Irradiation Assembly Condition. Selection of UNF for retention could include consideration of the post-irradiation assembly condition. Some assemblies exhibit assembly twist or bow after they are removed from the reactor. These conditions may indicate unusual stresses in the assembly structures. Such assemblies may be useful in the study of the long-term structural integrity of UNF. Additionally, some PWR assemblies are used in ways that result in significant cross-assembly burnup gradients. Such gradients may also indicate cross-assembly stresses in the grids that hold the assembly together.

Damaged or Reconstituted Fuel. A small fraction, 0.012 by mass through 2002,[5] of the UNF has been identified as damaged and has been either repaired or segregated. Inclusion of samples of such fuel would support research into fuel damage mechanisms.

Consolidated Fuel. A small fraction, 1.32E-5 by mass through 2002,[5] of the UNF has been disassembled and the removed fuel rods placed into consolidated fuel canisters.[20] Retained UNF should consider inclusion of consolidated fuel to support resolution of potential future issues that may arise.

3.2.3 Summary

Tables A-1 through A-4 provide summary information[5] that describes the commercial UNF inventory. The discussion in this section and the information in Appendix A are provided to give the reader an understanding of the complexity of the process needed to select a sufficient quantity of representative commercial UNF to retain for future RD&D efforts. With these complexities in mind, a set of selection criteria was developed and described in this section. Some of the selection criteria are focused on specific issues such as understanding and predicting clad integrity and those affecting fuel assembly long-term structural integrity, while others are focused on ensuring access is maintained to UNF representing the full range of parameters characterizing the UNF inventory to support resolution of potential future issues. At this point, it was decided to err on the side of inclusion, such that future refinements of the selection criteria might reduce the variety and amount of material for which access is retained. The selection criteria were grouped into the following two main categories: (1) assembly design and (2) assembly exposure and operating history. Recommendations for retention of UNF for future RD&D based on the selection criteria discussed above are provided in Section 5.

3.3 ALTERNATIVE FUEL CYCLES

The development of sustainable fuel cycles* is one of the four main R&D objectives for nuclear energy in the DOE-NE Roadmap.[2] Sustainable fuel cycle options are defined in the DOE-NE Roadmap as those that improve uranium resource utilization, maximize energy generation, minimize waste generation, improve safety, and limit proliferation risk. As stated in the DOE-NE Roadmap, the key challenge is to develop a suite of fuel cycle options that will enable future decision makers to make informed choices about how best to manage the UNF from reactors. The options for sustainable fuel cycles, as described in the DOE-NE Roadmap, include both once-through and recycle fuel cycles, where once-through options dispose of UNF while recycle options reprocess UNF so that some of the elements can be recovered and included in new fuel. Recycle fuel cycles dispose of high-level wastes, and may also dispose of UNF if all UNF is not reprocessed.

There are numerous technical issues to address in the development of alternative fuel cycle options and the supporting technologies, some of which can be studied using surrogate materials for UNF, and others that can only be investigated using actual UNF, such as the effects of prior irradiation, radiation, and

*Except where reference is made to specific aspects of the DOE-NE Roadmap, "alternative fuel cycles" is used in this report to refer to any and all possible future fuel cycles, including sustainable fuel cycles as they are defined in the DOE-NE Roadmap.

decay heat. As a consequence, to support the RD&D, there is a need to have representative UNF available to complete development and testing of candidate technologies, whether for extended storage, reprocessing, disposal, or advanced reactor fuel development.

When assessing the existing UNF inventory relative to retention needs to support alternative fuel cycles, there are two principal considerations – access to UNF to support

1. ongoing R&D of alternative fuel cycles, particularly those involving reprocessing and recycle, and

2. deployment of a potential future recycle fuel cycle, for which some portion of the existing inventory could have potential value that would be recovered by reprocessing.

Each of these considerations is discussed in the following subsections.

3.3.1 Used Nuclear Fuel to Support R&D

Development of alternative fuel cycle options will require RD&D in several areas, including separations technology development for processing UNF, especially for recovering certain elements from the UNF, and fuel form and reactor technology development for effectively using the recycled UNF material. As the technologies develop, it will become essential to test processing and fuel fabrication technologies with actual UNF to fully understand and address the various issues and complications that may arise when using actual UNF. For example, the radiation emitted by UNF can be substantial, being highest at discharge and decreasing steadily with time due to radioactive decay. The radiation from the UNF can have significant implications for process chemicals, shielding of facilities and equipment, and handling. Decay heat can also be an important issue, especially for processes that can accumulate heat-producing nuclides. The content of UNF, the chemical form of the elements in the UNF, and the physical form all need to be studied to ensure that the technologies will work as required. The material and the chemical and physical condition of the cladding may also influence the total amount recovered in processing, as well as the amount of material lost in the waste stream (e.g., in the form of undissolved solids) and the amount of post-processing waste.

The RD&D for alternative fuel cycle options will require access to sufficient amounts of UNF with appropriate characteristics. In considering the relevant UNF characteristics, it is important to again recognize that light water reactor (LWR) fuel has evolved over the past several decades, with increases in initial enrichment, increases in the discharge burnup, and changes in fuel assembly designs and materials, including increased use of integral burnable absorbers, and the isotopic content of the discharged UNF. Given that the alternative fuel cycles being investigated today may not be implemented for decades, this study asserts that it is important that any separations process testing be performed with UNF that is expected to be similar to that which would be available decades from now, consistent with the anticipated time frame for potential deployment of an alternative fuel cycle. As a result, it is expected that recently discharged UNF with characteristics most similar to projected future discharged UNF (e.g., high burnup, high initial enrichment, and modern fuel design) would be most useful to the RD&D program. At the same time, there is a potential need for UNF that has spent significant time in storage since there are fuel cycle options that use such storage as an integral part of the fuel cycle to take advantage of the change in composition resulting from radioactive decay.

To illustrate the variation in the composition of the commercial UNF assemblies in the UNF inventory through 2002, with respect to reactor type, discharge burnup, and post-irradiation cooling time, the ^{239}Pu equivalence[21] is plotted in Figure 16 and Figure 17 for a thermal and fast reactor, respectively. The ^{239}Pu equivalence is a comparative parameter that was developed such that all fuel with the same ^{239}Pu equivalence will achieve the same reactivity lifetime and discharge burnup and maintain similar local

power peaking factors and other safety-related fuel parameters. The ^{239}Pu equivalence is also a function of the subsequent reactor the plutonium will be used within. For a simple comparison, only two types of subsequent reactors were considered: a LWR that uses mixed oxide (MOX) fuel, Figure 16, and a fast breeder reactor similar to the Super-Phenix, Figure 17. The colors in the figures represent different discharge dates—blue being 1968 and red being 2002—while the symbols represent reactor type—square for PWR and round for BWR assemblies. From Figure 16 it can be seen that higher burnup fuels and correspondingly recently discharged fuel produced from BWR reactors have a ^{239}Pu equivalence for thermal reactors that is lower than lower burnup fuels.

From Figure 16 it can be estimated that future discharged fuel being recycled for MOX assemblies will have a lower ^{239}Pu equivalence for BWR reactor types but should have a similar ^{239}Pu equivalence for PWR fuels. In Figure 17, it can be seen that higher burnup fuels have a higher ^{239}Pu equivalence for fast reactors than the fuels with lower burnup. This is especially true for the PWR assemblies. From Figure 17 it can be estimated that future discharged fuel being recycled for fast reactor assemblies will have a higher ^{239}Pu equivalence for PWR and BWR reactor types.

Although the ^{239}Pu equivalence factor is shown here to illustrate the various influences on the fissile content of the UNF assemblies, it is just one of several factors to be considered when selecting UNF to support RD&D. The specific amount of UNF that would need to be retained is difficult to estimate. Experience suggests that engineering-scale demonstrations would typically be in the range of a few MTHM per year, perhaps as high as 50 MTHM/year, and could last for several years depending on the extent of engineering-scale testing that is required. A pilot plant to demonstrate commercial viability is expected to be in the range of up to a few hundred MTHM per year and could operate for as long as a decade. The ~2000 MTHM of UNF that is discharged annually from the current fleet of LWRs represents a continuous potential source from which retained material with characteristics of current vintage UNF could be replaced, as needed. The only category that could not be readily replaced is that of aged UNF. In that case, the UNF inventory would need to be examined for fuel of sufficiently high burnup, with a physical form at least similar to today's UNF, if not identical. Such fuel has been discharged within the past 10 years, but fuel older than 10 years tends to have considerably lower burnup (Figure 10), decreasing its similarity to the anticipated characteristics of UNF discharges decades from now.

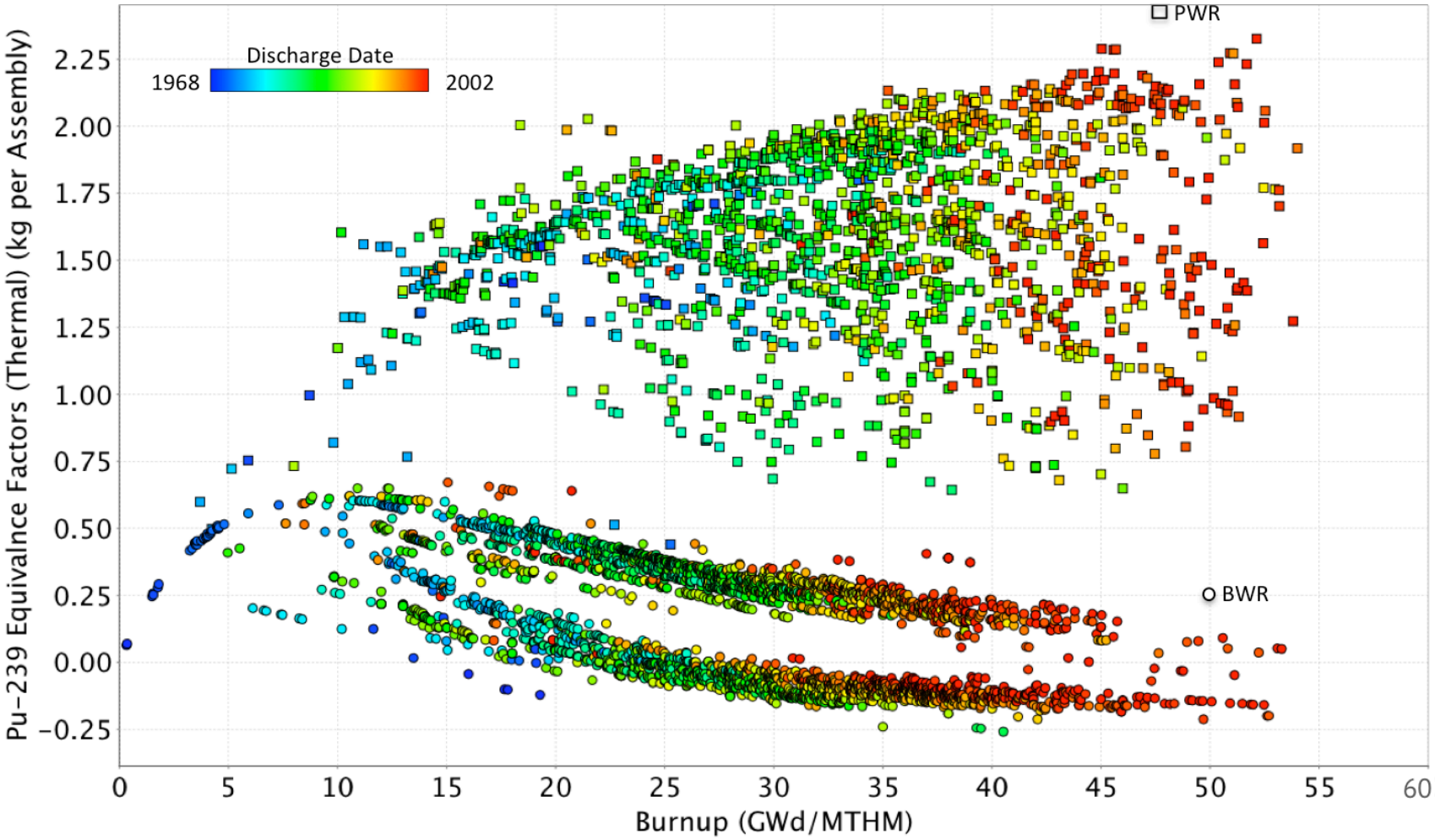

Figure 16. Plutonium-239 equivalence for a thermal reactor as a function of burnup, discharged date, and reactor type. *Source*: Ref. 22.

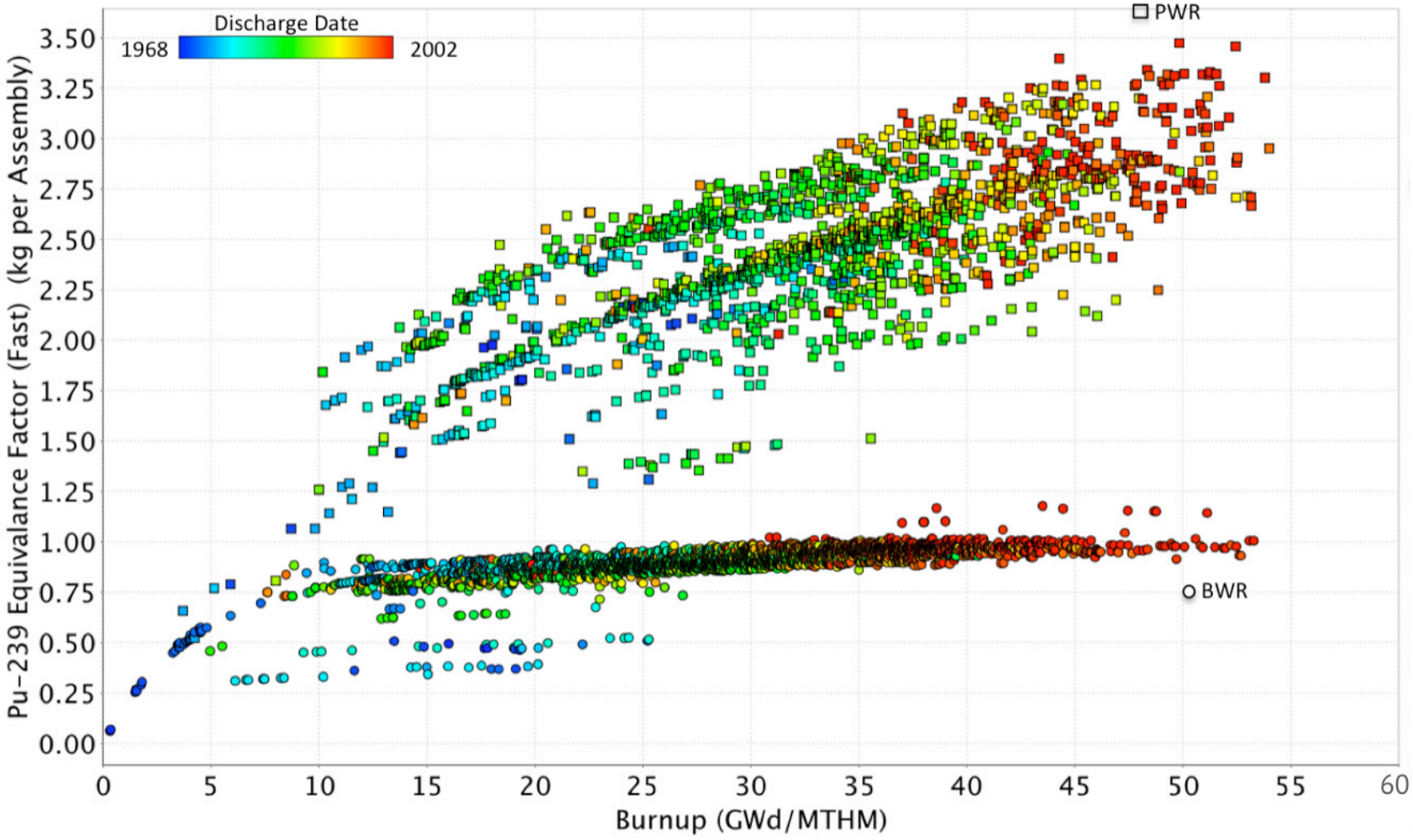

Figure 17. Plutonium-239 equivalence for a fast reactor as a function of burnup, discharged date, and reactor type. *Source*: Ref. 22.

3.3.2 Used Nuclear Fuel to Support Recycle Fuel Cycle Deployment

Depending on the outcome of R&D on alternative fuel cycles, as well as other nontechnical considerations, alternative fuel cycles may be deployed within the next few decades. If a recycle fuel cycle is selected for deployment, the existing UNF inventory could potentially be a resource for reprocessing. The question is whether, and how much of, the existing UNF inventory should be retained for production use in such recycle fuel cycles. To investigate this question, it is useful to consider the general characteristics of such fuel cycles, their need for UNF, and the potential deployment of these fuel cycles.

The current U.S. fleet of 104 operating reactors discharges ~2000 MTHM of UNF annually. The current inventory of commercial UNF, ~67,600 MTHM, is the result of reactor operation over the last ~50 years, although there were far fewer reactors in the early days of nuclear power. At the current rate of production, the current fleet will generate another ~67,600 MTHM of UNF over the next 30 years or so, a time frame that is similar to that anticipated for completing RD&D and moving forward with deployment of a recycle fuel cycle, if the decision were made to do so. This situation is shown in Figure 18, where it can be seen that the disposal of almost the entire current inventory of UNF would have no impact on the ability to accumulate new UNF prior to the potential deployment of a recycle fuel cycle. This figure shows the total current UNF inventory in 2011 and designates all but ~1700 MTHM for disposal. For UNF generated in subsequent decades, the figure identifies the material for disposal and retention assuming a constant discharge rate of 2000 MTHM/y, a recycling strategy using 5-y cooled UNF implemented by 2030, and a corresponding reprocessing rate so that the UNF inventory stabilizes, in this case at around 20,000 MTHM. Note that UNF is systematically retained for RD&D purposes prior to 2025, after which the UNF is retained principally for recycling. This is only one example deployment scenario for a recycle fuel cycle, and many others can be proposed, but this example illustrates the point that at the current generation rate for UNF, if a decision is made to move towards a recycle fuel cycle, there is ample time to accumulate a stockpile of UNF to support it. As a consequence, this study concludes that there is no compelling reason to retain any of the existing UNF inventory for production recycling purposes in the future.

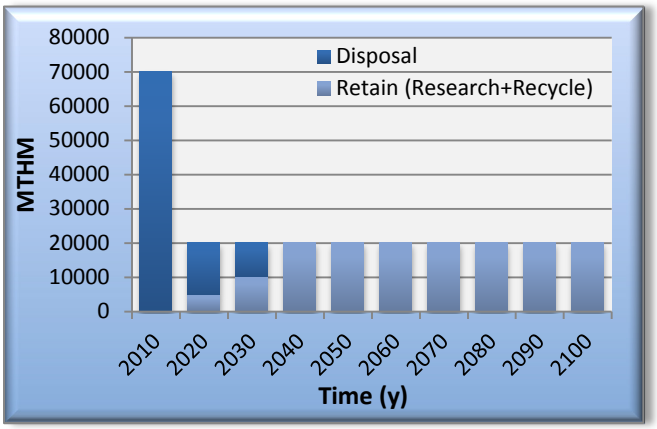

Figure 18. Categorization of UNF assuming current discharge rate and recycling beginning in 2030.

Another consideration for the use of UNF for recycle is related to the design optimization and operation of the reprocessing facility. The recycling plant will involve several steps in processing of the UNF with

the first process being receipt of the UNF and chopping operation that precedes separation of the fuel material from the cladding. The design of the front-end process must account for variations in the fuel assembly designs, including geometry, mass, and structure. To maximize the facility reliability and throughput, as well as to reduce the initial facility cost, it is advantageous to limit the range of fuel types that the facility must accommodate. As previously discussed, since the fuel designs are converging to a relatively few common designs, the current and future UNF discharges would have the most advantages for optimizing the front-end design and facility operations. Hence, the older fuel, and much of the current UNF inventory, would not be desirable feedstock as it differs from the large amount of available nearly uniform design UNF that will be discharged in the future.

It is useful to note that the only exception to the above conclusion is the case where a rapid deployment of certain fuel cycles would be anticipated. There are fuel cycles[23] based on deployment of high conversion or breeder reactors, where the ability to deploy the advanced reactors depends on the availability of elements that are present in the UNF, and having a greater stockpile of UNF may enable a more rapid deployment. One example of such a system would be the rapid deployment of fast reactors using plutonium as the initial start-up charge. These reactors require nominally 5–10 tonnes plutonium/GWe, which would amount to processing ~1000 MTHM of used LWR fuel. With ~2000 MTHM of LWR UNF being produced annually, fast reactor deployment of 2–4 GWe annually could be supported. If the rapid deployment were to exceed this growth rate, previous stockpiles would be necessary or enriched uranium would have to be substituted for plutonium start-up fuel. However, this would only be possible if reprocessing capability were rapidly deployed that significantly exceeds the current production rate of ~2000 MTHM per year.

As another specific example scenario in which fast reactors take on a prominent role, consider a fuel cycle option in which the United States deploys fast reactors after the year 2050, at which time it is expected that technology would be available for commercial deployment. The U.S. electricity demand is expected to grow at approximately 1% per year,[24] and assuming nuclear is to maintain its current market share of electricity, the U.S. nuclear capacity will double before 2100. In this example scenario, all of the newly built reactors that are constructed to address the growth requirements and to replace the closing LWR fleet after 2050 are fast reactors; until that time new LWRs are built. Even in this scenario it has been shown that there is sufficient plutonium available in the LWR UNF from 2020 onwards to fuel all of the future fast reactors as they reach equilibrium with self-sustaining plutonium recycle. This would require reprocessing of the LWR fuel to start several years prior to the first fast reactor coming online to develop sufficient material for reactor startup (Figure 19).

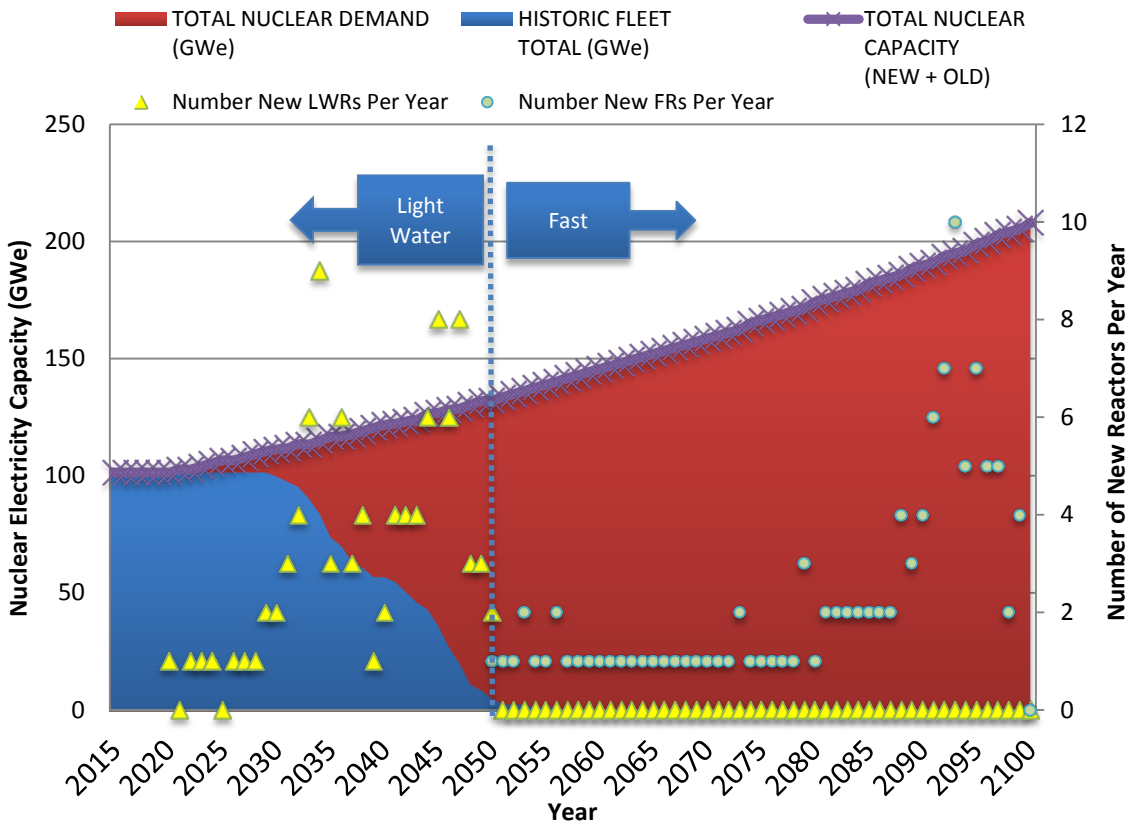

Figure 19. Predicted number of light water reactors and fast reactors required to match potential nuclear growth scenario. *Source*: Ref. 25.

While these example fast-reactor deployment scenario exceptions are in contradiction with several of our key assumptions (Section 3.1), the conclusion that the existing inventory of LWR UNF is not needed remains valid.

3.4 NATIONAL SECURITY

Highly enriched uranium UNF may be useful to support national security missions and represents a small fraction of the current UNF inventory (~50 MTHM with an enrichment greater than 90 wt % ^{235}U). This material represents U.S.-origin enriched uranium that is not subject to international consent agreements. For example, it could be used to offset the need for a dedicated enrichment plant to support national security missions. Given the special nature of this material, it is recommended that a study be conducted to evaluate the benefits of recovering this material.

4. CRITERIA FOR USED NUCLEAR FUEL CATEGORIZATION

Based on the assessment of UNF relative to retention needs discussed in the previous section, it is proposed that the current UNF inventory can be divided into the following three categories – disposal, research, and recycle. These categories and attributes and issues affecting categorization of the UNF inventory relative to these categories are discussed in this section.

4.1 USED NUCLEAR FUEL CATEGORIES

4.1.1 Disposal

This category is for excess material that is not needed for other purposes. For material in this category, it is judged that the liabilities associated with maintaining access to the material exceed the value to the nation, and that there is high confidence that this determination will not change in any reasonably foreseeable future scenario. Further, this category is defined to be consistent with The Nuclear Waste Policy Act[26] definition of "disposal" in that for material to be placed in this category, there is "no foreseeable intent of recovery" from disposal. Categorization of UNF for disposal does not require a determination that it has no value. In principle, all irradiated fuel has some potential value as an energy source. The determination instead supports a comprehensive national fuel cycle strategy.

4.1.2 Research

This category is for UNF material that may be needed to support the DOE-NE RD&D programs and objectives, as well as RD&D for the broader nuclear energy enterprise. Currently, retention of access to material in this category is anticipated for RD&D purposes to support UNF management (e.g., UNF storage, transportation, and disposal) and development of alternative fuel cycles as specified in the DOE-NE Roadmap. For any material placed in this category, it is judged that access to that material should be preserved to support RD&D programs.

4.1.3 Recycle/Recovery

This category is for UNF material that may be needed as feedstock for production-scale (beyond RD&D) recycling as part of a recycle fuel cycle, as well as UNF material that may be needed to support national security interests. This category includes commercial UNF for recycle to commercial systems as well as recovery of strategic materials, such as the HEU UNF. For any material placed in this category, it is judged that access to that material should be preserved for recycling or recovery purposes.

4.2 ATTRIBUTES AND ISSUES AFFECTING CATEGORIZATION

4.2.1 Disposal

The primary attribute that defines UNF categorized for disposal is, at the most basic level, that it not be categorized as warranting retention for other purposes. Further, as discussed in the subsection that follows, that there is no foreseeable intent of recovery from disposal following emplacement. Various types of UNF may have different characteristics that have the potential to affect disposal system performance (e.g., UNF with high thermal output may require additional consideration in disposal system operations or design), but ultimately, a repository must be capable of receiving any material for which there is no alternative disposition pathway. Past analyses[27-31] of a range of repository concepts in the United States and elsewhere indicate that robust isolation can be achieved for a broad range of UNF types. In this work, categorization of UNF for retention will primarily be based on other attributes, as described in the following sections.

4.2.1.1 Retrievability

The Nuclear Waste Policy Act[26] defines "disposal" to mean "the emplacement in a repository of high-level radioactive waste, spent nuclear fuel, or other highly radioactive material with no foreseeable intent of recovery, whether or not such emplacement permits the recovery of such waste." Usage in this report is entirely consistent with this definition: the categorization of UNF as being suitable for direct disposal in a repository carries an implicit acknowledgment that there are no foreseeable circumstances under which the DOE might choose to retrieve the material from the repository for subsequent reuse.

Regardless of the determination that there is "no foreseeable intent of recovery" of UNF once it has been emplaced in a repository, there are legal and regulatory requirements that material be retrievable from repositories. Specifically, the NRC requires in 10 CFR 60.111(b)(1)[a] that "the geologic repository operations area shall be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated, unless a different time period is specified by the Commission." The Environmental Protection Agency (EPA), at 40 CFR 191.14(f), took a slightly different approach, by requiring that "disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period after disposal," but further noted that "the intent of this provision was not to make recovery of waste easy or cheap, but merely possible in case some future discovery or insight made it clear that the wastes needed to be relocated."[32] In addition, with the Blue Ribbon Commission's observed that these requirements "are not intended for the purpose of retaining easy access to emplaced materials for possible later recovery or reuse."[33] The DOE will not emplace material in a repository if there is intent to reuse it at a later date. It will also ensure that any repository meets legal and regulatory requirements for retrievability if necessary.

4.2.2 Research

For RD&D to support UNF management, including storage, transportation, and disposal, the most useful UNF would be that which represents the full range of parameters characterizing the current discharged inventory. Due to the significant diversity in the current UNF inventory, a set of selection criteria was developed and grouped into the following two main categories: (1) assembly design and (2) assembly exposure and operating history. The characteristics that are most relevant are described in Section 3.2.2 and comprise the fuel assembly design, including materials, exposure conditions and discharge burnup, and cooling time and post-irradiation storage conditions. Access to a sufficient quantity of representative commercial UNF is needed to support planned R&D efforts and to be available to support addressing questions or issues that may arise in the future.

For RD&D to support development of alternative nuclear fuel cycles, per the DOE-NE Roadmap, the most useful UNF would be that which best represents UNF expected to be discharged one or more decades from now, at about the time when a recycle fuel cycle might be deployed. Older fuel can also be used for RD&D of the separations and treatment technologies and advanced fuel development at the laboratory and engineering scales. The characteristics that are most relevant are the fuel type and characteristics, such as inclusion of burnable absorbers, the discharge burnup, and the cooling time. This would provide UNF of the appropriate composition, and with the corresponding physical fuel conditions, cladding conditions, and such that would make technology development and testing relevant for use with future UNF discharges.

[a]Note that currently applicable regulations may change as a new U.S. policy regarding nuclear waste management evolves.

4.2.3 Recycle/Recovery

For production-scale recycling as part of a sustainable full-recycle fuel cycle strategy, there are a number of considerations that influence the decision on the UNF feedstock characteristics that are most useful and/or preferred. These include, but are not limited to the following.

- characteristics of the new fuel to be produced
- isotopic composition of the UNF feedstock, which dictates energy content and impacts facility design and operations in terms of decay heat, radiation dose rates, and criticality safety
- variability of the isotopic compositions in the UNF feedstock, for example, due to variability in assembly initial enrichment, burnup, and decay time, which impacts operations to satisfy tolerance requirements for the new fuel to be produced
- total fissile mass per UNF feedstock assembly
- physical variability of the UNF feedstock, for example, due to variability in assembly mass, cladding materials, non-fuel hardware components, and possible degradation (e.g., oxidation of cladding), which impacts head-end design, operations and operational throughput, and facility reliability
- availability of UNF feedstock for the intended lifetime of the facility
- accessibility to the UNF feedstock, for example, accessibility and operations associated with using UNF assemblies loaded into a variety of dry storage cask systems may be different from using UNF assemblies taken directly from wet storage

Each of these considerations impacts the cost of the recycling facility in terms of initial design, licensing, construction, and operation.[34,35]

The timing selected for initial separation of UNF is especially important and has been studied extensively. Older UNF (e.g., discharged 30 or more years prior to recycling) has distinct advantages in head-end processing as the decay of fission products minimizes issues with fission gas capture, decay heat, radiation dose rates, and waste management.[36] On the other hand, UNF loses fissile ^{241}Pu to ^{241}Am with aging, significantly reducing the energy content of the UNF. The loss of ^{241}Pu has resulted in the standard commercial approach of recycling UNF to make MOX LWR fuel following a post-irradiation cooling time of approximately 5 years. The discharge isotopic composition of a Westinghouse Electric (WE) 17×17 assembly with initial enrichment of 4.5 wt % that has accumulated 45 GWd/MTU burnup is shown in Figure 20 for reference purposes.

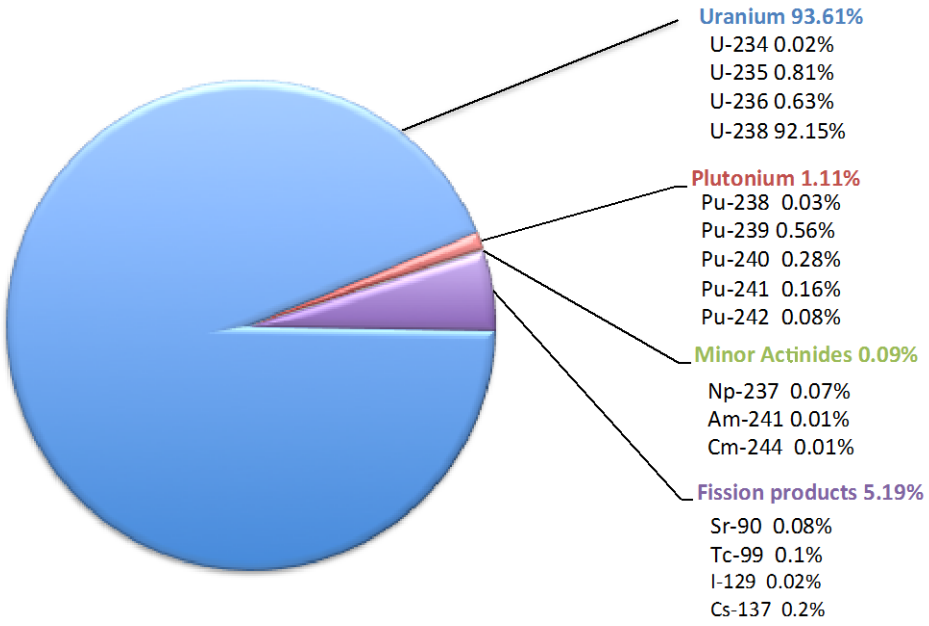

Figure 20. Discharge isotopic composition of a WE 17×17 assembly with initial enrichment of 4.5 wt % that has accumulated 45 GWd/MTU burnup.

The isotopic composition of recycled plutonium is a function of the total burnup, reactor type, initial enrichment, and, as mentioned, time after discharge of the UNF. As seen in Figure 21, plutonium continues to increase with burnup; however, only ^{239}Pu and ^{241}Pu are fissile, and although dependent on a number of factors, those isotopes generally do not continue to increase significantly at higher burnup. In addition, ^{241}Pu has a relatively short half-life (14.4 years).

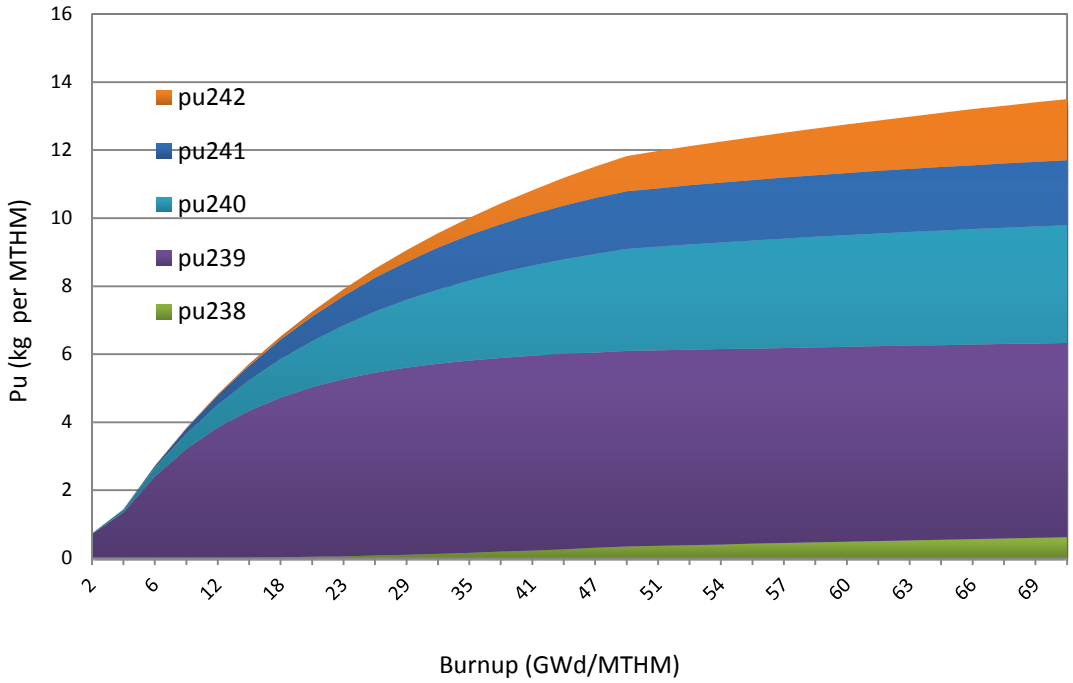

Figure 21. Isotopic composition of used nuclear fuel as a function of burnup for a generic PWR 17×17 assembly for zero cooling time.

In a previous study[37] that investigated prioritization of criteria for selecting UNF for recycling, plutonium concentrations as a function of both burnup and decay time were correlated with a parameter called the support ratio. The support ratio was defined to be the amount of discharged LWR UNF that would need to be recycled to produce the same energy content within the reactor. The higher the support ratio, the larger the mass of fuel that would need to be reprocessed to obtain the equivalent quantity of fissile material. The authors compared the support ratio for both PWR and BWR UNF and showed that even though longer burnup increases the production of undesirable plutonium isotopes, such as ^{242}Pu, it also results in the highest fissile content. It was also shown that fuels with shorter cooling times following discharge also contain higher fissile content. From an energy content perspective, these results confirm the desirability of reprocessing high-burnup UNF with short cooling times. As the current inventory of UNF tends to have lower burnup and longer cooling time, as compared to recently and/or to-be-discharged UNF, on a per mass basis, the quantity of fissile material in the current inventory of UNF is generally lower (on a per-assembly basis) than that of future discharged UNF. This lower content implies the need to process more fuel assemblies to recover a given amount of fissile material, which will result in additional processing cost. For this reason, the newly available or future UNF is attractive for advanced recycling. The newly available or future UNF can, however, put some stringent requirements on the design and operation of the recycling facilities to ensure workers' safety from the higher radiation from such UNF.

From an engineering and operational point of view, uniformity between assemblies is also an important aspect to take into consideration. This is because the fuel recycling facility and the fuel fabrication facility will require remote handling and automation for most of the processes. Remote handling and automation add a complexity to the overall process; therefore, having an input stream with very similar characteristics can decrease the facility design, construction, and operational costs and potentially greatly

improve operational reliability and throughput. Another important consideration is the fissile mass per assembly—the higher the fissile mass, the fewer the number of assemblies that must be processed to obtain a given fissile mass of new fuel, which improves operational throughput and facility efficiency. Figure 22 shows the variability in initial uranium mass in the 22 assembly classes present in the current UNF inventory. Given that the new PWR reactor designs for which COL applications have been submitted (i.e., AP1000, U.S. EPR, and U.S. APWR), all intend to use the same assembly lattice size (i.e., 17×17) and length (14 ft), and the high initial uranium mass per assembly associated with the 17×17 lattice size, as shown in Figure 22. Future discharges of high-burnup 17×17 assemblies appear to be a good potential source for recycling feedstock.

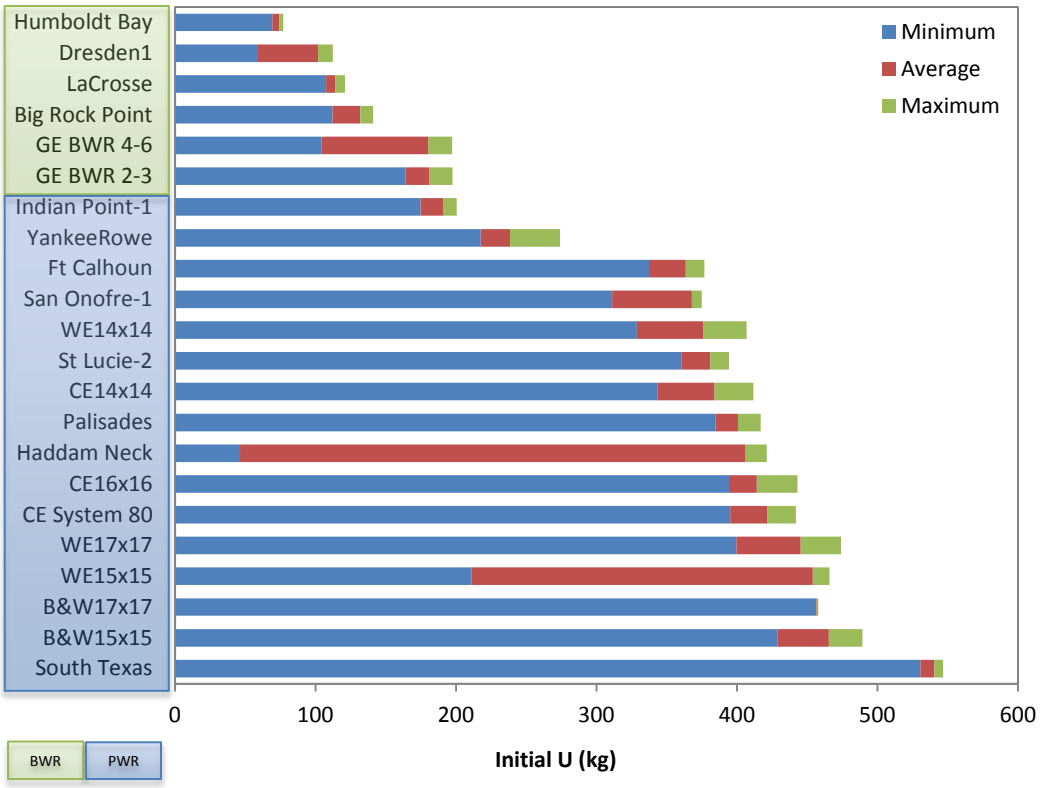

Figure 22. Distribution of assembly initial uranium mass by assembly class in the commercial UNF inventory as of 2002. *Source*: Ref. 5.

Based on the preceding discussion and previous studies, it is judged that the most useful material for production-scale recycling has the following attributes: high burnup, relatively short cooling time, and, to the extent possible, uniformity in fuel design and discharge characteristics. An inherent assumption in this judgment is that the recycling is focused on recovering the plutonium energy resource. Recovery of residual uranium was considered, but given that the residual fissile (^{235}U) uranium content in currently discharged UNF is near or below the content available in natural uranium and the current cost and availability of natural uranium, recovery of uranium from UNF is not anticipated to be a key factor in a future decision on pursuing production-scale recycling.

If a decision is made in the future to proceed with production-scale recycling, the above discussion supports the assumption that, to be sustainable, the fuel cycle would be based on UNF discharges at that time. In other words, that a future recycling facility would not likely be designed and optimized for UNF

feedstock that is no longer being produced. Part of the basis for this assumption is that the United States is currently discharging ~2000 MTHM annually, and hence by the time production-scale recycling would be deployed, the United States will have plenty of additional UNF material that is better suited to production-scale recycling than the current UNF inventory (i.e., high burnup, shorter cooling time, and more uniform design and discharge characteristics). Therefore, the most useful UNF material is that which best represents the UNF expected to be discharged at the time when the recycle fuel cycle is to be deployed.

For recovery, the potential strategic value of the material is considered, particularly for national security interests. The primary attribute that defines UNF categorized for recovery is the residual ^{235}U enrichment. Domestically generated UNF is not subject to international consent agreements, and hence material with high residual ^{235}U enrichment could be recovered from HEU UNF and used to offset the need for a dedicated enrichment plant to support national security missions. For example, HEU UNF could be processed to recover the HEU, which could then be down-blended to produce enriched material to support national security missions.

5. RESULTS OF CATEGORIZATION

Based on the assessment of UNF relative to retention needs, time frames in which recycle fuel cycles could be realistically deployed, and possible uses to support national security interests, the current (as of 2011) UNF inventory is categorized in this section according to the three categories described Section 4.1.

5.1 DISPOSAL

The current UNF in this category is that which is categorized as not warranting retention for other purposes, and hence is the total current UNF inventory minus the material designated for either the research or recycle/recovery categories.

The ~2500 MTHM of DOE-owned UNF is currently designated by the DOE Office of Environmental Management (EM) for disposal and was included in this report for completeness. With the exception of the small fraction that contains HEU, the DOE-owned UNF was not independently assessed here. Until and unless determined otherwise, the ~2500 MTHM of DOE-owned UNF is designated for disposal, except for the small fraction that contains HEU.

As a result of consideration of the needs of the DOE-NE RD&D programs and objectives, as well as RD&D for the broader nuclear energy enterprise, time frames in which recycle fuel cycles could be realistically implemented, and possible uses to support national security interests, it is proposed that ~68,450 MTHM (~66,000 MTHM of commercial and ~2500 MTHM of DOE owned) of the current (as of 2011) UNF inventory should be placed in the disposal category and permanently disposed, without the need to make fuel retrievable from disposal for reuse or research purposes.

5.2 RESEARCH

In the following subsections, it is estimated that access to up to ~1,700 MTHM of the current (as of 2011) commercial UNF inventory be retained to support RD&D for UNF management and alternative fuel cycles.

5.2.1 Used Nuclear Fuel Management

As was discussed in Section 3.2, there is a recognized need to maintain access to a sufficient quantity of representative samples of commercial UNF to support UNF management, including storage, transportation, and disposal. Selection of UNF assemblies for retention is complicated by the use of a wide variety of fuel assembly designs in the various PWR and BWR designs, the significant variations in exposure and operating history, and the need to retain to sufficient quantities of these variations to enable reliable statistical analyses. With consideration of these variations and potential RD&D needs to support UNF management, a set of selection criteria were developed and described in Section 3.2.2. Based on these selection criteria, it is recommended that access be retained to each of the significant fuel assembly design variations in the current inventory, which will provide representative samples and sufficient quantities from each reactor type (i.e., BWR and PWR) and design (i.e., Westinghouse, Combustion Engineering, B&W, General Electric, etc.). For each of these significant fuel assembly design variations, it is recommended that access be retained to UNF assemblies representing the full range of important design variations, such as cladding materials and integral burnable absorbers, fuel assembly burnup values, and post-irradiation cooling times. Finally, for selected assembly designs, it is recommended to retain access to assemblies that experienced varying reactor operating conditions and post-irradiation storage conditions, and assemblies with varying post-irradiation physical conditions of interest (e.g., bowing, other forms of damage, and rod consolidation). It is important to note that a number of these

selection criteria are overlapping. For example, UNF assemblies of a given assembly type that span the representative range of burnup values and cooling times may also cover some or all of the range of operating conditions and post-irradiation storage conditions of interest.

For reasons related to practicality of operations, it may not be possible, particularly in the near term, to select individual UNF assemblies for access retention. Rather, to retain access to UNF assemblies of interest, it may be necessary to retain access to dry storage casks that are loaded with the UNF assemblies of interest. Given the manner in which dry storage casks are typically loaded (e.g., to balance total package thermal limits), loaded casks are expected to provide some of the variability (e.g., variations in fuel burnup, cooling times, and fuel assembly design variations) recommended above for UNF management. However, if UNF assembly selection is based on loaded casks (i.e., for a cask that has one or more assemblies of interest, the entire cask load is retained), it is expected that the total amount of UNF that would be retained will be greater than if selection was based on individual assemblies. Furthermore, most of the UNF-related issues of interest to UNF management are related to fuel rod materials and their performance,[12] and hence RD&D to resolve these issues may only require access to fuel rods, as opposed to fuel assemblies. Therefore, retention of UNF assemblies, as opposed to rods, will also contribute to the retention of more UNF material than is actually needed for the RD&D. This may actually be viewed as a positive aspect, given that it will result in some, potentially significant, amount of excess material that will help to provide assurance that any future retrievability from disposal will not be necessary. As the RD&D programs proceed, future implementation efforts may work to enable the retention of individual rods, as opposed to assemblies, and assemblies, as opposed to casks, according to the specific RD&D material needs.

With these practicalities in mind, recommendations on the amount of UNF for which access should be retained to support UNF management RD&D are presented in Table 1. For high-capacity rail casks, the low end of the range (i.e., ~200 MTHM) may be acceptable if the selection process includes provisions for identifying and custom loading of casks to optimize the representation of the selected fuel assemblies. For example, for a given lattice, one large cask might be filled with assemblies representing the design and operational variations experienced at a plant, another large cask could be loaded with otherwise similar assemblies having assembly burnup values spread over the relevant range, and a third cask with assemblies having cooling times spread over the relevant range. Of course, this low-end estimate would require considerable coordination with industry and may not fully accommodate future RD&D needs. The high end of the range (i.e., ~1146 MTHM) may be necessary if candidate casks must be selected from already-loaded casks and/or if it is decided that access to some of each of the reactor-specific assembly types must be retained. Note, for example, that some of the reactor-specific fuel types, such as Yankee Rowe and La Crosse, are fully loaded in dry storage casks. Hence, the high end of the range may be needed to support retention of all relevant design and operational variations and a reasonably complete distribution of assembly discharge burnup values and post-irradiation cooling times. At this point, it is decided to err on the side of inclusion, such that future refinements of the selection criteria and RD&D needs and/or coordination with industry or a future consolidated storage site to enable access to specific assemblies and/or rods might reduce the variety and amount of material for which access is retained. Therefore, based on this assessment, it is suggested that access to up to ~1146 MTHM of the current commercial UNF be retained to support UNF management RD&D.

Table 1. Estimated mass of UNF for which access should be retained to support UNF management R&D

PWR UNF									
Assembly design	**Average MTHM per assembly**	**MTHM per truck cask (4 assemblies per cask)[a]**	**Number of truck casks**	**Total MTHM for truck casks**	**MTHM per rail cask (32 assemblies per cask)**	**Number of rail casks**	**Total MTHM for rail casks**		
CE 14×14	0.384	1.536	15	23.04	12.29	2 to 10	24.58	to	122.88
CE 16×16	0.417	1.668	15	25.02	13.34	2 to 10	26.69	to	133.44
B&W 15×15	0.465	1.860	15	27.90	14.88	2 to 10	29.76	to	148.80
WE 14×14	0.376	1.504	15	22.56	12.03	2 to 10	24.06	to	120.32
WE 15×15	0.454	1.816	15	27.24	14.53	2 to 10	29.06	to	145.28
WE 17×17	0.445	1.780	15	26.70	14.24	2 to 10	28.48	to	142.40
All PWR			90	152.46		12 to 60	162.62	to	813.12
BWR UNF									
Assembly design	**Average MTHM per assembly**	**MTHM per truck cask (9 assemblies per cask)[a]**	**Number of truck casks**	**Total MTHM for truck casks**	**MTHM per rail cask (68 assemblies per cask)**	**Number of rail casks**	**Total MTHM for rail casks**		
GE 6×6	0.097	0.873	7	6.11	6.60	1 to 6	6.60	to	39.58
GE 7×7	0.191	1.719	7	12.03	12.99	1 to 6	12.99	to	77.93
GE 8×8	0.180	1.620	7	11.34	12.24	1 to 6	12.24	to	73.44
GE 9×9	0.171	1.539	7	10.77	11.63	1 to 6	11.63	to	69.77
GE 10×10	0.176	1.584	7	11.09	11.97	1 to 6	11.97	to	71.81
All BWR			35	51.35		5 to 30	55.42	to	332.52
PWR & BWR UNF									
BWR & PWR			125	203.81		17 to 90	218.04	to	1145.64

[a]Capacity based on the GA-4 and GA-9 cask designs.[38]

5.2.2 Alternative Fuel Cycles

As was discussed in Section 3.3, there is a recognized need to maintain access to representative samples and sufficient quantities of commercial UNF to support RD&D for alternative fuel cycle options. The amount of UNF that would need to be retained for such RD&D is difficult to estimate. Experience suggests that engineering-scale demonstrations would typically be in the range of a few MTHM per year, perhaps as high as 50 MTHM/year, and could last for several years depending on the extent of engineering-scale testing that is required. A pilot plant to demonstrate commercial viability is expected to be in the range of up to a few hundred MTHM per year, and could operate for as long as a decade. Considering the potential need for up to 50 MTHM/y over the next decade to support RD&D and potential engineering-scale testing, it is suggested that access to up to ~500 MTHM of commercial UNF be retained to support alternative fuel cycle RD&D. The UNF selected for access retention should be a mix of that which best represents UNF expected to be discharged one or more decades from now and older fuel that can be more easily used for RD&D of separations and treatment technologies and advanced fuel development. It is noted that ~2000 MTHM of UNF is discharged annually from the current fleet of LWRs, and hence the ~500 MTHM is considered an upper estimate for retention at this time. It is further noted that the amount of material retained for UNF management RD&D may include sufficient margin to cover some portion of the RD&D needs for alternative fuel cycles. Finally, given the desired attributes of the UNF material for recycling in an alternative fuel cycle, discussed in Section 4.2.3, it may be decided in the future that the current commercial UNF for which access is retained to support advance fuel cycle R&D should be replaced at appropriate intervals with future discharged UNF.

5.3 RECYCLE/RECOVERY

As discussed above, it is not anticipated that any of the current inventory of UNF would be needed to support utilization in a deployed recycle fuel cycle. History suggests that a decision to deploy such a fuel cycle is likely decades away and dependent on the outcome of current RD&D activities such as the Nuclear Fuel Cycle Evaluation and Screening[39] and the development of advanced separations technologies, as well as a consensus on the need to deploy an alternative fuel cycle on an industrial scale. Assuming that such RD&D indicates promise for a recycle fuel cycle sufficient to support a decision to move forward with implementation, once the decision is made, it would require at least a decade or more to design, license, and construct the facilities to support such a fuel cycle. Based on the current UNF production rate, the anticipated deployment schedule would allow sufficient time to accumulate the needed inventory to support such a fuel cycle. Therefore, it is suggested that none of the current commercial UNF be retained to support production-scale recycle at this time.

As discussed above there is up to ~50 MTHM of HEU UNF that includes material with high residual ^{235}U enrichment. This material represents U.S.-origin enriched uranium that is not subject to international consent agreements, and hence may be useful in support of national security missions. Given the special nature of this material, it is recommended that all ~50 MTHM of this material be placed into the recycle/recovery category.

5.4 SUMMARY

The results of the categorization discussed in the above sections are summarized in Table 2. The estimated total amount in the Research category (~1,646 MTHM) includes ~1146 MTHM to support UNF management RD&D (Section 5.2.1) and ~500 MTHM to support alternative fuel cycles RD&D (Section 5.2.2), and represents ~2% (by mass) of the total UNF inventory. The estimated total amount in the Recycle/Recovery category corresponds to the ~50 MTHM of HEU UNF to support national security missions. The remainder of the total inventory, ~98% (by mass), is assigned to the Disposal category.

Table 2. Summary of UNF categorization results (units are MTHM)

UNF Type	Total	Disposal	Research	Recycle/Recovery
Commercial	67,600	65,954	1,646	0
DOE owned	2,500	2,500	0	0
HEU	50	0	0	50
Total	70,150	68,454	1,646	50
Percent of total		97.58	2.35	0.07

6. CONCLUSIONS

The DOE-NE FCT program conducted a review and technical assessment of the current inventory of domestic discharged UNF to determine if it can be separated into different, distinguishable categories relative to disposition options and, if so, to quantitatively differentiate the UNF inventory relative to the defined categories. The technical assessment considered discharged UNF from commercial nuclear electricity generation and defense and research programs and determined that the current (as of 2011) UNF inventory can be divided into the following three distinguishable categories:

1. Disposal – excess material that is not needed for other purposes;

2. Research – material needed for RD&D purposes to support waste management (e.g., UNF storage, transportation, and disposal) and development of alternative fuel cycles (e.g., separations and advanced fuels); and

3. Recycle/Recovery – material with inherent and/or strategic value.

The technical assessment subsequently developed a set of key assumptions and attributes relative to the various disposition options and then used the assumptions and attributes to categorize the current UNF inventory. As a result of consideration of RD&D needs, time frames in which recycle fuel cycles could be realistically implemented, and possible uses to support national security interests, it is estimated that up to ~1700 MTHM of existing UNF, including up to ~ 50 MTHM of HEU UNF, should be considered for retention to support RD&D needs and national security interests. The quantity was determined based on RD&D needs and practical considerations for access to a representative sample of the diverse commercial UNF inventory to support UNF storage, transportation, and disposal; access to UNF to support fuel cycle technology development; and a sufficient margin to provide assurance that future retrievability from disposal will not be necessary. The assumptions used for this assessment are consistent with the DOE-NE Roadmap; specifically, the time to complete the needed RD&D places commercial reprocessing availability no sooner than the 2030 time frame. The remainder, ~68,450 MTHM or ~98% of the total current inventory by mass, can proceed to permanent disposal without the need to ensure retrievability for reuse or research purposes. This finding does not preclude any decision about alternative fuel cycle options, including those with potential recycling of commercial UNF, since the ~2000 MTHM that is generated annually could provide the feedstock needed for deployment of alternative fuel cycles.

The main conclusion of this assessment is not the specific amounts or specific assemblies for retention and disposal but rather that access to some small fraction of the existing UNF should be retained, while the remainder can proceed to disposal without the need to ensure retrievability for reuse or research purposes. Because a repository is not anticipated to be available for more than a decade, time is available to refine, if needed, the specific amounts and select specific assemblies as the RD&D programs proceed and the associated UNF material needs are better defined.

7. SUGGESTIONS FOR FURTHER WORK

During the course of this assessment the following areas for further work were identified.

- *Evaluate the issues and potential benefits associated with the recovery of HEU UNF* – Although the HEU UNF represents only a small fraction of the current UNF inventory, it could be a valuable resource for a number of applications. Given the special nature of this material, it is recommended that a study be conducted to evaluate the benefits and issues associated with recovering this material.

- *Assess the DOE-owned UNF relative to the defined categories* – the DOE-owned UNF (~2500 MTHM) is currently designated by DOE-EM for disposal. With the exception of the small fraction that contains HEU, the DOE-owned UNF was not independently assessed here. Given that some of the fuel types in the DOE-owned UNF inventory may have relevance to advanced reactor RD&D, it may be prudent to reassess the DOE-owned UNF relative to the identified categories..

- *Refinement of the specific quantity and specific UNF rods/assemblies for retention of access* – the focus of the current work was to determine if the domestic UNF inventory could be separated into different, distinguishable categories relative to disposition options and, if so, to quantitatively differentiate the UNF inventory relative to the defined categories. The result was a set of defined categories and corresponding mass estimates. For this work, it was decided to err on the side of inclusion in the Research category, such that future refinements of the selection criteria and RD&D needs and/or coordination with industry or a future consolidated storage site to enable access to specific assemblies and/or rods might reduce the variety and amount of material for which access is retained. Therefore, as the RD&D programs proceed, for example, the Nuclear Fuel Cycle Evaluation and Screening Activity and UFDC activities, it is recommended that further work be performed to refine the specific quantity and specific UNF rods/assemblies for retention of access.

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APPENDIX A

COMMERCIAL USED NUCLEAR FUEL CHARACTERISTICS

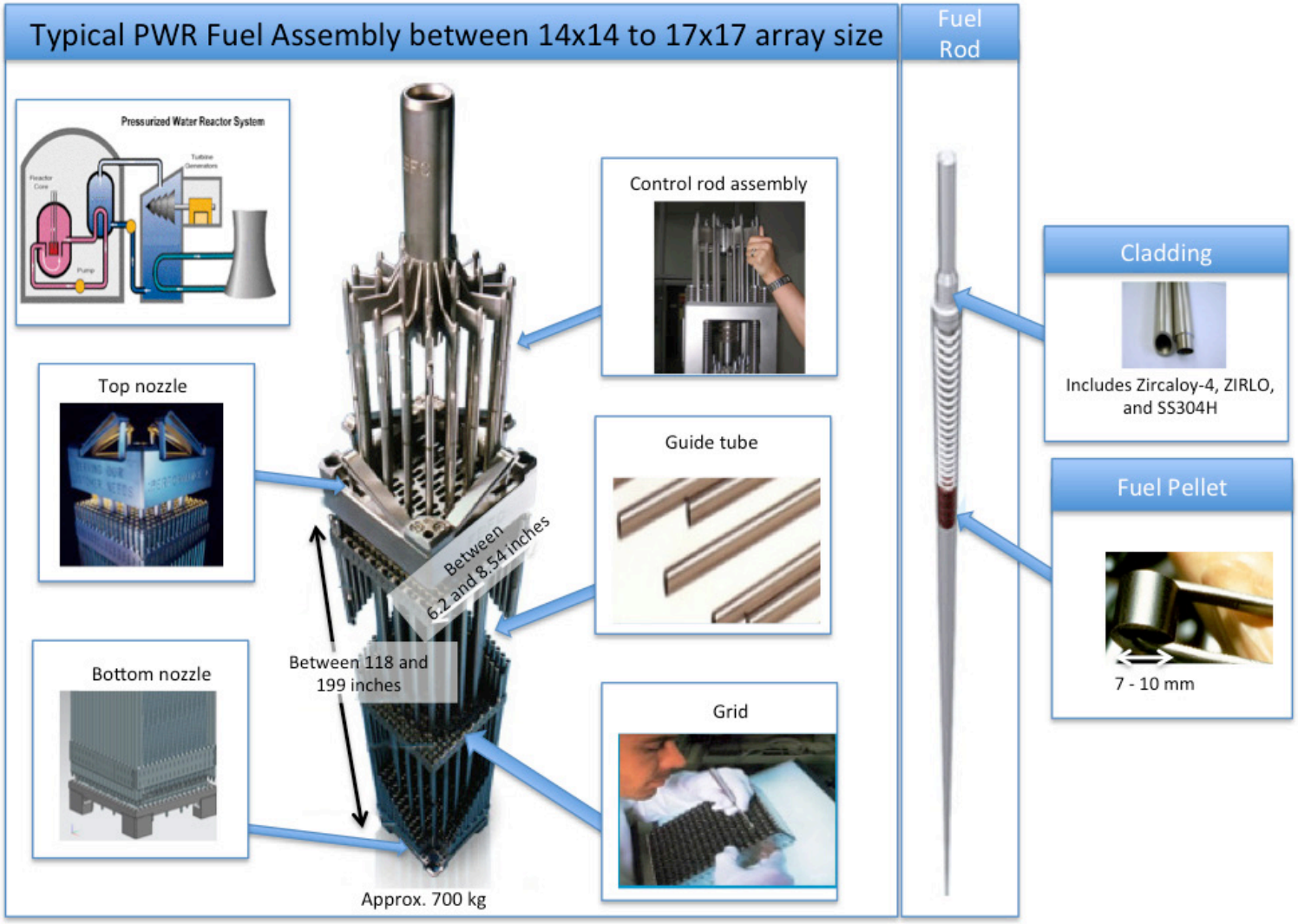

Figure A-1. Typical PWR fuel assembly.

Table A-1. Physical characteristics of pressurized water reactor assembly classes [Ref. 3]

Assembly class	Array size	Mfr. code	Version	Assembly code	Length (in.)	Width (in.)	Clad material
B&W 15×15	15×15	B&W	B&W Mark B	B1515B	165.7	8.54	Zircaloy-4
			B&W Mark B10	B1515B10	165.7	8.54	Zircaloy-4
			B&W Mark B3	B1515B3	165.7	8.54	Zircaloy-4
			B&W Mark B4	B1515B4	165.7	8.54	Zircaloy-4
			B&W Mark B4Z	B1515B4Z	165.7	8.54	Zircaloy-4
			B&W Mark B5	B1515B5	165.7	8.54	Zircaloy-4
			B&W Mark B5Z	B1515B5Z	165.7	8.54	Zircaloy-4
			B&W Mark B6	B1515B6	165.7	8.54	Zircaloy-4
			B&W Mark B7	B1515B7	165.7	8.54	Zircaloy-4
			B&W Mark B8	B1515B8	165.7	8.54	Zircaloy-4
			B&W Mark B9	B1515B9	165.7	8.54	Zircaloy-4
			B&W Mark BGD	B1515BGD	165.7	8.54	Zircaloy-4
			B&W Mark BZ	B1515BZ	165.7	8.54	Zircaloy-4
		WE	WE	B1515W	165.7	8.54	not available
B&W 17×17	17×17	B&W	B&W Mark C	B1717B	165.7	8.54	Zircaloy-4
CE 14×14	14×14	ANF	ANF	C1414A	157.0	8.10	Zircaloy-4
		CE	CE	C1414C	157.0	8.10	Zircaloy-4
		WE	WE	C1414W	157.0	8.10	Zircaloy-4
CE 16×16	16×16	CE	CE	C1616CSD	176.8	8.10	Zircaloy-4
CE System 80	16×16	CE	CE System 80	C8016C	178.3	8.10	Zircaloy-4
WE 14×14	14×14	ANF	ANF	W1414A	159.8	7.76	Zircaloy-4
		ANF	ANF Top Rod	W1414ATR	159.8	7.76	Zircaloy-4
		B&W	B&W	W1414B	159.8	7.76	not available
		WE	WE LOPAR	W1414WL	159.8	7.76	Zircaloy-4
		WE	WE OFA	W1414WO	159.8	7.76	Zircaloy-4
		WE	WE Std	W1414W	159.8	7.76	Zircaloy-4
WE 15×15	15×15	ANF	ANF	W1515A	159.8	8.44	Zircaloy-4
			ANF HT	W1515AHT	159.8	8.44	not available
			ANF Part Length	W1515APL	159.8	8.44	not available
		WE	LOPAR	W1515WL	159.8	8.44	Zircaloy-4
			OFA	W1515WO	159.8	8.44	Zircaloy-4
			WE Std	W1515W	159.8	8.44	Zircaloy
			WE Vantage 5	W1515WV5	159.8	8.44	not available

Table A-1 (continued)

Assembly class	Array size	Mfr. code	Version	Assembly code	Length (in.)	Width (in.)	Clad material
WE 17×17	17×17	ANF	ANF	W1717A	159.8	8.44	Zircaloy-4
		B&W	B&W Mark B	W1717B	159.8	8.44	not available
		WE	WE	W1717WRF	159.8	8.44	not available
			WE	W1717WVJ	159.8	8.44	not available
			WE LOPAR	W1717WL	159.8	8.44	Zircaloy-4
			WE OFA	W1717WO	159.8	8.44	Zircaloy-4
			WE Pressurized	W1717WP	159.8	8.44	not available
			WE Vantage	W1717WV	159.8	8.44	not available
			WE Vantage +	W1717WV+	159.8	8.44	ZIRLO
			WE Vantage 5	W1717WV5	159.8	8.44	Zircaloy-4
			WE Vantage 5H	W1717WVH	159.8	8.44	not available
South Texas	17×17	WE	WE	WST17W	199.0	8.43	Zircaloy-4
Ft. Calhoun	14×14	ANF	ANF	XFC14A	146.0	8.10	not available
		CE	CE	XFC14C	146.0	8.10	Zircaloy-4
		WE	WE	XFC14W	146.0	8.10	not available
Haddam Neck	15×15	B&W	B&W SS	XHN15B	137.1	8.42	SS-304
			B&W Zir	XHN15BZ	137.1	8.42	Zircaloy
		GA	Gulf SS	XHN15HS	137.1	8.42	SS
			Gulf Zir	XHN15HZ	137.1	8.42	Zircaloy
		NU	NUM SS	XHN15MS	137.1	8.42	SS
			NUM Zir	XHN15MZ	137.1	8.42	Zircaloy
		WE	WE	XHN15W	137.1	8.42	SS-304
			WE Zir	XHN15WZ	137.1	8.42	not available
Indian Point-1	13×14	WE	WE	XIP14W	138.8	6.27	SS
Palisades	15×15	ANF	ANF	XPA15A	147.5	8.20	Zircaloy-4
		CE	CE	XPA15C	147.5	8.20	Zircaloy-4
St. Lucie-2	16×16	CE	CE	XSL16C	158.2	8.10	Zircaloy-4
San Onofre-1	14×14	WE	WE	XSO14W	137.1	7.76	SS-304
			WE D	XSO14WD	137.1	7.76	not available
			WE M	XSO14WM	137.1	7.76	not available
Yankee Rowe	15×16	ANF	ANF	XYR16A	111.8	7.62	Zircaloy-4
		CE	CE	XYR16C	111.8	7.62	Zircaloy-4
		UNC	UNC	XYR16U	111.8	7.62	not available
	17×18	WE	WE	XYR18W	111.8	7.62	SS

Note: some characteristics of more recently discharged UNF (post-1999) have not yet been provided.

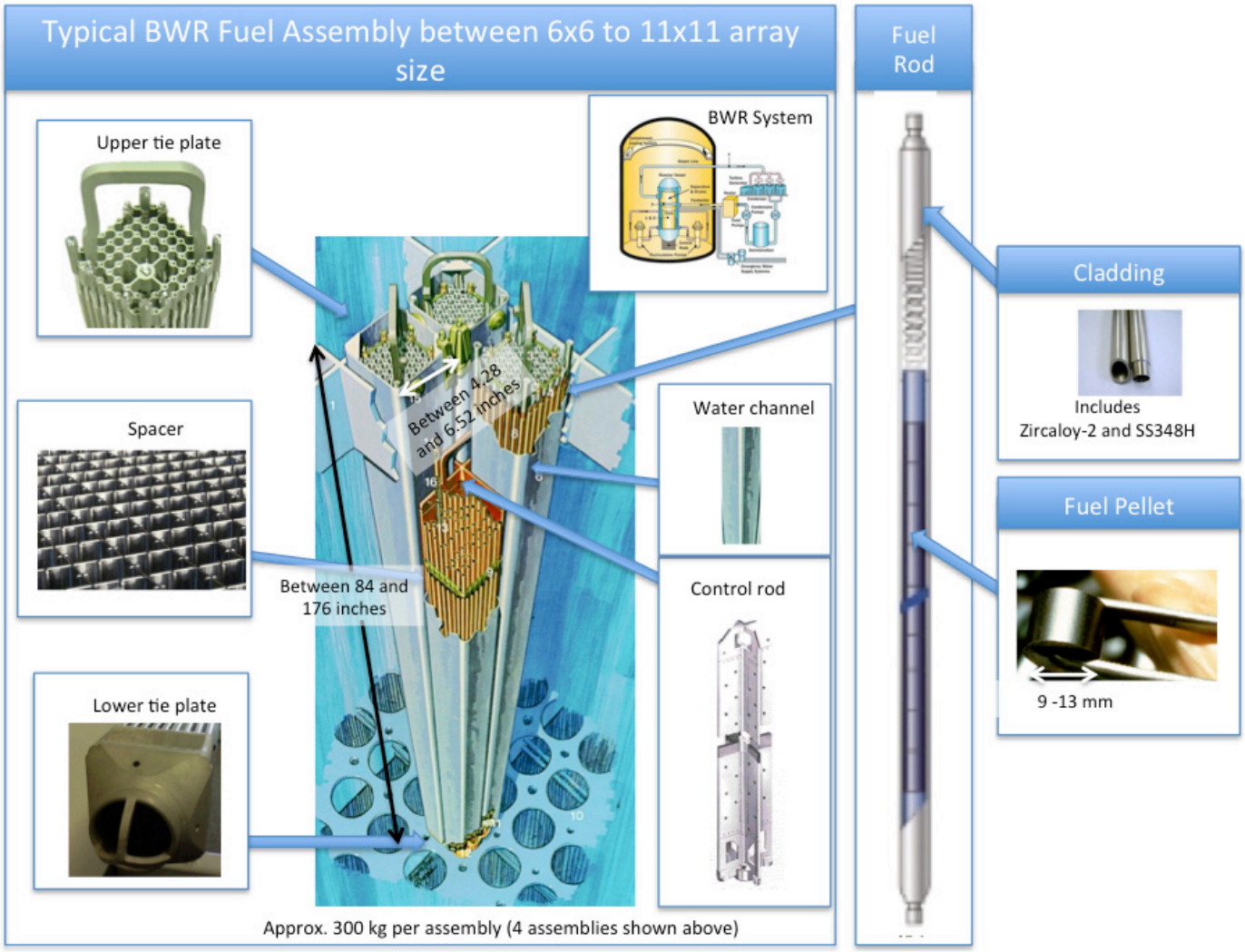

Figure A-2. Typical BWR fuel assembly.

Table A-2. Physical characteristics of boiling water reactor assembly classes [Ref 3]

Assembly class	Array size	Mfr. code	Version	Assembly code	Length (in.)	Width (in.)	Clad material
GE BWR/ 2,3	7×7	ANF	ANF	G2307A	171.2	5.44	Zircaloy-2
	8×8	ANF	ANF	G2308A	171.2	5.44	Zircaloy-2
	9×9	ANF	ANF	G2309A	171.2	5.44	Zircaloy-2
			ANF IX	G2309AIX	171.2	5.44	Zircaloy-2
	8×8	ANF	ANF Pressurized	G2308AP	171.2	5.44	Zircaloy-2
		GE	GE-10	G2308G10	171.2	5.44	Zircaloy-2
	9×9	GE	GE-11	G2309G11	171.2	5.44	Zircaloy-2
	7×7	GE	GE-2a	G2307G2A	171.2	5.44	Zircaloy-2
			GE-2b	G2307G2B	171.2	5.44	Zircaloy-2
			GE-3	G2307G3	171.2	5.44	Zircaloy-2
	8×8	GE	GE-4	G2308G4	171.2	5.44	Zircaloy-2
			GE-5	G2308G5	171.2	5.44	Zircaloy-2
			GE-7	G2308G7	171.2	5.44	NA
			GE-8a	G2308G8A	171.2	5.44	Zircaloy-2
			GE-8b	G2308G8B	171.2	5.44	Zircaloy-2
			GE-9	G2308G9	171.2	5.44	Zircaloy-2
			GE-Barrier	G2308GB	171.2	5.44	Zircaloy-2
			GE-Pressurized	G2308GP	171.2	5.44	Zircaloy-2
	NA	NA	NA	9X9IXQFA	171.2	5.44	NA
GE BWR/ 4-6	9×9	ANF	ANF	G4609A	176.2	5.44	Zircaloy-2
	10×10	ANF	ANF	G4610A	176.2	5.44	NA
	9×9	ANF	ANF 9-5	G4609A5	176.2	5.44	Zircaloy-2
			ANF 9X	G4609A9X	176.2	5.44	Zircaloy-2
			ANF IX	G4609AIX	176.2	5.44	Zircaloy-2
	10×10	ANF	ANF IX	G4610AIX	176.2	5.44	NA
	9×9	ANF	ANF X+	G4609AX+	176.2	5.44	NA
	8×8	ANF	ANF-Pressurized	G4608AP	176.2	5.44	Zircaloy-2
	NA	AREVA	NA	ATRIUM10	176.2	5.44	Zircaloy-2[a]

Table A-2 (continued)

Assembly class	Array size	Mfr. code	Version	Assembly code	Length (in.)	Width (in.)	Clad material
GE BWR/ 4-6 (Continued)	10×10	ABB	CE	G4610C	176.2	5.44	NA
	8×8	GE	GE-10	G4608G10	176.2	5.44	Zircaloy-2
			GE-11	G4608G11	176.2	5.44	NA
	9×9	GE	GE-11	G4609G11	176.2	5.44	Zircaloy-2
	8×8	GE	GE-12	G4608G12	176.2	5.44	NA
	10×10	GE	GE-12	G4610G12	176.2	5.44	Zircaloy-2
	9×9	GE	GE-13	G4609G13	176.2	5.44	Zircaloy-2
	10×10	GE	GE-14	G4610G14	176.2	5.44	NA
	7×7	GE	GE-2	G4607G2	176.2	5.44	Zircaloy-2
			GE-3a	G4607G3A	176.2	5.44	Zircaloy-2
			GE-3b	G4607G3B	176.2	5.44	Zircaloy-2
	8×8	GE	GE-4a	G4608G4A	176.2	5.44	Zircaloy-2
			GE-4b	G4608G4B	176.2	5.44	Zircaloy-2
			GE-5	G4608G5	176.2	5.44	Zircaloy-2
			GE-8	G4608G8	176.2	5.44	Zircaloy-2
			GE-9	G4608G9	176.2	5.44	Zircaloy-2
			GE-Barrier	G4608GB	176.2	5.44	Zircaloy-2
			GE-Pressurized	G4608GP	176.2	5.44	Zircaloy-2
		WE	WE	G4608W	176.2	5.44	Zircaloy-2
Big Rock Point	9×9	ANF	ANF	XBR09A	84	6.52	Zircaloy-2
	11×11	ANF	ANF	XBR11A	84	6.52	Zircaloy-2
	7×7	GE	GE	XBR07G	84	6.52	NA
	8×8	GE	GE	XBR08G	84	6.52	NA
	9×9	GE	GE	XBR09G	84	6.52	Zircaloy-2
	11×11	GE	GE	XBR11G	84	6.52	Zircaloy-2
		NFS	NFS	XBR11N	84	6.52	NA
Dresden-1	6×6	ANF	ANF	XDR06A	134.4	4.28	Zircaloy-2
		GE	GE	XDR06G	134.4	4.28	Zircaloy-2
	7×7	GE	GE SA-1	XDR07GS	134.4	4.28	NA
	8×8	GE	GE PF Fuels	XDR08G	134.4	4.28	NA
	6×6	GE	GE Type III-B	XDR06G3B	134.4	4.28	NA
			GE Type III-F	XDR06G3F	134.4	4.28	NA
			GE Type V	XDR06G5	134.4	4.28	NA
		UNC	UNC	XDR06U	134.4	4.28	NA

Table A-2 (continued)

Assembly class	Array size	Mfr. code	Version	Assembly code	Length (in.)	Width (in.)	Clad material
Humboldt Bay	6×6	ANF	6 × 6 ANF	XHB06A	95	4.67	Zircaloy
		GE	GE	XHB06G	95	4.67	Zircaloy-2
	7×7	GE	GE Type II	XHB07G2	95	4.67	Zircaloy
La Crosse	10×10	AC	AC	XLC10L	102.5	5.62	SS348H
		ANF	ANF	XLC10A	102.5	5.62	SS348H

Note: some characteristics of more recently discharged UNF (post-1999) have not yet been provided.

Table A-3. Assembly types and their main characteristics as of December 31, 2002 [Ref. 3]

Reactor type	Manufacturer code	Assembly code	Initial uranium loading (kg/assembly)		Enrichment (U^{235} wt %)			Burnup (MWd/MTU)	
			Avg.	Max.	Min.	Avg.	Max.	Avg.	Max.
BWR	not available	9X9IXQFA	170.713	170.800	3.25	3.25	3.25	39,166	39,248
BWR	AC	XLC10L	120.160	121.034	3.63	3.77	3.94	14,419	21,532
BWR	ANF	G2307A	181.574	183.797	2.56	2.64	2.65	24,256	27,826
BWR	ANF	G2308A	174.624	184.355	2.39	2.66	3.13	28,814	36,826
BWR	ANF	G2308AP	172.753	173.132	2.82	2.83	2.83	34,366	34,826
BWR	ANF	G2309A	168.097	169.520	2.78	3.10	3.15	35,941	40,818
BWR	ANF	G2309AIX	169.185	170.059	3.25	3.31	3.82	39,151	43,778
BWR	ANF	G4608AP	176.175	176.800	2.62	2.88	3.40	31,248	35,518
BWR	ANF	G4609A	172.970	174.700	0.72	3.42	3.73	36,933	47,000
BWR	ANF	G4609A5	176.147	177.000	2.90	3.28	3.55	36,536	43,555
BWR	ANF	G4609A9X	169.155	176.800	2.53	2.87	3.11	36,880	43,330
BWR	ANF	G4609AIX	174.788	177.000	3.00	3.58	3.94	24,156	36,777
BWR	ANF	G4609AX+	167.264	167.277	3.13	3.14	3.15	39,239	40,457
BWR	ANF	G4610A	176.900	176.900	3.94	3.94	3.94	38,207	39,000
BWR	ANF	G4610AIX	175.000	175.000	3.39	3.39	3.39	37,706	38,009
BWR	ANF	XBR09A	127.687	131.406	3.45	3.48	3.52	20,981	22,811
BWR	ANF	XBR11A	130.237	133.174	3.13	3.42	3.82	22,716	34,212
BWR	ANF	XDR06A	95.206	95.478	2.23	2.23	2.24	4,907	5,742
BWR	ANF	XHB06A	69.734	73.800	2.35	2.40	2.41	9,037	22,377
BWR	ANF	XLC10A	108.657	109.609	3.68	3.69	3.71	15,017	20,126
BWR	AREVA	ATRIUM10	176.900	176.900	3.94	3.94	3.94	38,406	39,000
BWR	ABB	G4610C	175.683	176.300	2.51	3.29	3.62	38,133	42,640
BWR	GE	G2307G2A	194.902	197.604	2.07	2.10	2.11	16,775	24,902
BWR	GE	G2307G2B	193.203	197.400	1.65	2.15	2.62	16,384	29,728
BWR	GE	G2307G3	187.419	189.105	1.96	2.41	2.60	25,420	38,861
BWR	GE	G2308G10	172.225	173.512	3.10	3.25	3.56	33,988	43,977
BWR	GE	G2308G4	183.991	185.496	2.19	2.51	2.76	26,087	40,523
BWR	GE	G2308G5	176.971	177.628	2.39	2.66	2.82	29,009	33,597
BWR	GE	G2308G7	178.520	179.400	2.96	2.97	2.99	31,570	35,894
BWR	GE	G2308G8A	175.695	179.584	2.55	3.09	3.40	34,848	44,933
BWR	GE	G2308G8B	172.590	178.000	2.96	3.19	3.39	36,400	42,518
BWR	GE	G2308G9	172.017	173.108	2.85	3.18	3.48	37,268	42,295
BWR	GE	G2308GB	177.983	180.060	2.62	2.80	3.39	32,014	43,381
BWR	GE	G2308GP	177.145	179.200	2.08	2.77	3.01	29,317	38,139

Table A-3 (continued)

Reactor type	Manufacturer code	Assembly code	Initial uranium loading (kg/assembly)		Enrichment (U^{235} wt %)			Burnup (MWd/MTU)	
			Avg.	Max.	Min.	Avg.	Max.	Avg.	Max.
BWR	GE	G2309G11	165.650	169.500	3.10	3.56	3.78	40,522	45,117
BWR	GE	G4607G2	194.729	197.334	1.09	1.56	2.50	9,362	11,829
BWR	GE	G4607G3A	187.455	189.141	1.10	2.33	2.51	21,058	32,188
BWR	GE	G4607G3B	189.925	191.542	1.10	2.31	2.51	21,948	30,831
BWR	GE	G4608G10	177.778	186.094	2.63	3.24	3.70	36,695	44,343
BWR	GE	G4608G11	170.786	171.000	3.38	3.38	3.38	35,194	42,551
BWR	GE	G4608G12	180.873	181.484	3.69	3.71	3.99	32,069	34,462
BWR	GE	G4608G4A	183.931	185.221	2.19	2.62	2.99	24,931	43,430
BWR	GE	G4608G4B	186.709	187.900	2.10	2.31	2.76	21,362	32,941
BWR	GE	G4608G5	183.007	185.366	0.70	2.36	3.01	23,964	38,224
BWR	GE	G4608G8	179.801	185.854	2.95	3.19	3.40	34,905	44,640
BWR	GE	G4608G8B	178.000	178.000	3.36	3.37	3.39	35,174	38,396
BWR	GE	G4608G9	177.738	185.789	1.51	3.23	3.88	36,492	47,062
BWR	GE	G4608GB	184.636	186.653	0.71	2.53	3.25	26,297	45,986
BWR	GE	G4608GP	183.195	186.888	0.70	2.38	3.27	23,112	42,428
BWR	GE	G4609G11	170.123	178.136	1.46	3.56	4.14	40,351	65,149
BWR	GE	G4609G13	171.417	172.912	3.24	3.85	4.17	42,045	53,636
BWR	GE	G4610G12	176.100	182.141	3.12	3.98	4.20	44,175	52,735
BWR	GE	G4610G14	179.127	180.402	4.01	4.11	4.24	5,868	8,915
BWR	GE	G4806G10	178.400	178.400	3.06	3.06	3.06	34,473	36,591
BWR	GE	XBR07G	131.500	133.000	2.88	2.88	2.88	1,643	1,690
BWR	GE	XBR08G	112.500	113.000	2.85	2.85	2.85	4,546	7,027
BWR	GE	XBR09G	137.088	141.000	3.51	3.58	3.62	15,092	22,083
BWR	GE	XBR11G	124.500	132.000	3.11	3.46	3.63	22,802	24,997
BWR	GE	XDR06G	111.352	111.352	1.47	1.47	1.47	23,522	23,522
BWR	GE	XDR06G3B	101.610	102.520	1.83	1.83	1.83	18,632	27,106
BWR	GE	XDR06G3F	102.049	102.876	2.25	2.25	2.25	22,132	28,138
BWR	GE	XDR06G5	105.857	112.257	2.26	2.26	2.26	21,095	25,886
BWR	GE	XDR07GS	59.000	59.000	3.10	3.10	3.10	29,000	29,000
BWR	GE	XDR08G	99.714	99.714	1.95	1.95	1.95	25,287	25,287
BWR	GE	XHB06G	76.355	77.000	2.35	2.43	2.52	17,170	22,876
BWR	GE	XHB07G2	76.325	77.100	2.08	2.11	2.31	18,187	20,770
BWR	NFS	XBR11N	128.991	134.414	2.16	2.83	3.51	18,940	21,850
BWR	UNC	XDR06U	102.021	103.441	1.83	2.24	2.26	17,685	26,396
BWR	WE	G4608W	156.696	171.403	2.69	2.85	3.01	28,041	33,140

Table A-3 (continued)

Reactor type	Manufacturer code	Assembly code	Initial uranium loading (kg/assembly)		Enrichment (U^{235} wt %)			Burnup (MWd/MTU)	
			Avg.	Max.	Min.	Avg.	Max.	Avg.	Max.
PWR	ANF	C1414A	380.870	400.000	0.30	3.50	4.32	38,899	50,871
PWR	ANF	W1414A	378.274	406.840	0.71	3.42	4.50	37,500	56,328
PWR	ANF	W1414ATR	362.788	368.011	2.39	3.38	3.57	38,168	46,000
PWR	ANF	W1515A	428.888	434.792	2.01	3.00	3.60	33,344	49,859
PWR	ANF	W1515AHT	434.546	438.074	3.51	4.08	4.59	45,441	56,922
PWR	ANF	W1515APL	307.361	310.073	1.23	1.55	1.88	27,971	37,770
PWR	ANF	W1717A	413.845	460.540	2.43	4.19	4.77	45,291	53,958
PWR	ANF	XFC14A	353.345	358.811	3.50	3.57	3.80	37,205	46,048
PWR	ANF	XPA15A	396.674	408.040	1.50	3.17	4.05	34,362	51,486
PWR	ANF	XYR16A	233.555	237.300	3.49	3.78	4.02	29,034	35,088
PWR	B&W	B1515B	463.398	465.480	2.74	3.57	3.62	40,407	50,128
PWR	B&W	B1515B10	476.778	489.299	3.24	3.90	4.73	44,417	56,880
PWR	B&W	B1515B3	463.845	465.830	1.08	2.42	2.84	21,036	32,267
PWR	B&W	B1515B4	464.285	474.853	0.90	2.91	4.06	29,534	57,000
PWR	B&W	B1515B4Z	463.735	466.305	3.22	3.84	3.95	39,253	51,660
PWR	B&W	B1515B5	468.250	468.250	3.13	3.13	3.13	38,017	39,000
PWR	B&W	B1515B5Z	464.421	465.176	3.20	3.22	3.23	36,016	42,328
PWR	B&W	B1515B6	462.495	464.403	3.22	3.47	3.66	41,790	49,383
PWR	B&W	B1515B7	463.244	464.513	3.48	3.51	3.55	42,059	48,738
PWR	B&W	B1515B8	464.864	468.560	3.29	3.65	4.01	42,692	54,000
PWR	B&W	B1515B9	463.566	467.566	3.29	3.96	4.76	44,097	53,952
PWR	B&W	B1515BGD	429.552	430.255	3.92	3.92	3.92	49,027	58,310
PWR	B&W	B1515BZ	463.410	466.279	3.05	3.47	4.68	37,441	54,023
PWR	B&W	B1717B	456.722	457.929	2.64	2.84	3.04	29,517	33,904
PWR	B&W	W1414B	383.157	383.157	3.22	3.22	3.22	24,398	24,465
PWR	B&W	W1717B	455.799	466.688	2.00	3.84	4.60	40,741	54,014
PWR	B&W	XHN15B	409.913	415.060	3.00	3.99	4.02	33,776	37,833
PWR	B&W	XHN15BZ	363.921	368.072	3.40	3.80	3.91	34,278	42,956
PWR	CE	C1414C	382.437	408.508	1.03	3.20	4.48	33,597	56,000
PWR	CE	C1616CSD	413.912	442.986	1.87	3.62	4.63	37,916	63,328
PWR	CE	C8016C	421.468	442.000	1.92	3.57	4.27	38,490	56,312
PWR	CE	XFC14C	362.313	376.842	1.39	2.96	3.95	32,130	52,125
PWR	CE	XPA15C	412.442	416.780	1.65	2.47	3.06	16,020	33,630
PWR	CE	XSL16C	381.018	394.400	1.72	3.44	4.28	38,807	54,838
PWR	CE	XYR16C	228.766	233.400	3.51	3.80	3.92	24,282	35,999

Table A-3 (continued)

Reactor type	Manufacturer code	Assembly code	Initial uranium loading (kg/assembly)		Enrichment (U^{235} wt %)			Burnup (MWd/MTU)	
			Avg.	Max.	Min.	Avg.	Max.	Avg.	Max.
PWR	GA	XHN15HS	406.163	406.163	3.99	3.99	3.99	32,151	32,151
PWR	GA	XHN15HZ	362.863	362.863	3.26	3.26	3.26	18,546	18,546
PWR	NU	XHN15MS	405.979	406.992	3.66	3.66	3.66	28,324	28,324
PWR	NU	XHN15MZ	370.776	371.039	2.95	2.95	2.95	25,643	25,643
PWR	UNC	XYR16U	238.573	241.300	3.96	3.99	4.02	27,461	31,986
PWR	WE	B1515W	461.819	464.763	3.90	4.06	4.22	36,993	49,075
PWR	WE	C1414W	403.483	411.719	2.70	3.15	3.76	30,039	37,781
PWR	WE	W1414W	393.896	403.683	2.26	3.04	3.47	27,315	39,723
PWR	WE	W1414WL	399.092	405.809	2.27	3.07	3.41	31,940	47,932
PWR	WE	W1414WO	355.724	369.265	0.99	3.92	4.95	44,730	69,452
PWR	WE	W1515W	451.193	458.091	2.21	3.00	3.35	29,324	41,806
PWR	WE	W1515WL	455.236	465.600	1.85	2.98	3.80	30,874	55,385
PWR	WE	W1515WO	460.764	465.747	1.91	3.53	4.60	39,071	56,138
PWR	WE	W1515WV5	457.793	462.934	2.99	3.92	4.80	37,556	53,056
PWR	WE	W1717WL	461.323	469.200	1.60	3.12	4.40	32,340	58,417
PWR	WE	W1717WO	425.107	459.433	1.60	3.05	4.02	32,690	53,000
PWR	WE	W1717WP	417.069	417.878	3.73	4.59	4.81	50,707	58,237
PWR	WE	W1717WRF	455.497	456.735	4.00	4.18	4.42	45,530	48,037
PWR	WE	W1717WV	425.399	426.042	4.21	4.38	4.41	44,263	48,385
PWR	WE	W1717WV+	424.010	465.469	1.61	4.16	4.66	45,430	61,685
PWR	WE	W1717WV5	424.269	430.925	1.49	4.01	4.95	43,872	56,570
PWR	WE	W1717WVH	461.954	473.962	2.11	3.87	4.95	41,081	55,496
PWR	WE	W1717WVJ	461.518	465.200	3.71	3.99	4.40	43,922	46,847
PWR	WE	WST17W	540.480	546.600	1.51	3.38	4.41	35,926	54,399
PWR	WE	XFC14W	374.055	376.000	0.27	3.75	4.25	38,521	51,971
PWR	WE	XHN15W	415.557	421.227	3.02	3.59	4.00	27,922	35,196
PWR	WE	XHN15WZ	384.894	386.689	4.20	4.39	4.60	14,321	19,376
PWR	WE	XIP14W	191.152	200.467	2.83	4.12	4.36	16,471	27,048
PWR	WE	XSO14W	368.153	374.885	3.16	3.87	4.02	27,232	39,275
PWR	WE	XSO14WD	373.323	373.643	4.01	4.01	4.02	18,259	18,424
PWR	WE	XSO14WM	311.225	311.225	0.71	0.71	0.71	19,307	19,636
PWR	WE	XYR18W	273.350	274.100	4.94	4.94	4.94	25,484	31,755

Table A-4. Summary of UNF characteristics from which representative samples may be selected [Ref. 5]

Assembly code	Lattice	Number of assemblies	Average initial kgU	Minimum final assay average BU (MWd/MTU)	Maximum final assay average BU (MWd/MTU)	Minimum assay average initial enrichment (wt %)	Maximum assay average initial enrichment (wt %)	Minimum cooling time thru 2010 (years)	Maximum cooling time thru 2010 (years)	Manu-facturer	Assay length (in.)
C1414A	14×14	1383	380.87	2000	50871	0.3	4.32	8.3	26.8	ANF	157
C1414C	14×14	4198	382.43	2768	56000	1.02	4.48	8.9	36.5	CE	157
C1414W	14×14	552	403.48	7339	37781	2.69	3.76	14.1	27.6	WE	157
W1414A	14×14	1018	378.27	24961	56328	0.71	4.5	9.3	33.7	ANF	159.8
W1414ATR	14×14	288	362.78	23144	46000	2.39	3.57	18.9	26.3	ANF	159.8
W1414B	14×14	2	383.15	24330	24465	3.22	3.22	33.7	33.7	B&W	159.8
W1414W	14×14	603	393.89	5582	39723	2.25	3.47	24.8	39.9	WE	159.8
W1414WL	14×14	1429	399.09	10774	47932	2.26	3.4	16.7	38.3	WE	159.8
W1414WO	14×14	2108	355.72	12670	69452	0.99	4.95	8.1	27.8	WE	159.8
XFC14A	14×14	192	353.34	24119	46048	3.5	3.8	18.9	26.8	ANF	146
XFC14C	14×14	418	362.31	7936	52125	1.39	3.95	9.8	35.9	CE	146
XFC14W	14×14	229	374.05	10492	51971	0.27	4.25	8.7	14.2	WE	146
XIP14W	14×14	160	191.15	3704	27048	2.83	4.36	36.2	38.0	WE	138.8
XSO14W	14×14	657	368.15	6800	39275	3.15	4.02	18.1	40.2	WE	137.1
XSO14WD	14×14	4	373.32	18154	18424	4.01	4.01	18.1	18.1	WE	137.1
XSO14WM	14×14	4	311.22	19061	19636	0.71	0.71	37.6	37.6	WE	137.1
B1515B	15×15	103	463.39	4286	50128	2.74	3.62	8.2	14.2	B&W	165.7
B1515B10	15×15	681	476.76	28791	56880	3.24	4.73	8.2	15.2	B&W	165.7
B1515B3	15×15	181	463.84	8652	32267	1.07	2.83	16.7	32.8	B&W	165.7
B1515B4	15×15	4136	464.28	10809	57000	0.9	4.06	8.2	36.2	B&W	165.7
B1515B4Z	15×15	170	463.73	33119	51660	3.21	3.95	9.3	18.7	B&W	165.7
B1515B5	15×15	58	468.25	38000	39000	3.13	3.13	16.2	17.8	B&W	165.7
B1515B5Z	15×15	29	464.42	34116	42328	3.2	3.23	17.7	19.0	B&W	165.7

Table A-4 (continued)

Assembly code	Lattice	Number of assemblies	Average initial kgU	Minimum final assay average BU (MWd/MTU)	Maximum final assay average BU (MWd/MTU)	Minimum assay average initial enrichment (wt %)	Maximum assay average initial enrichment (wt %)	Minimum cooling time thru 2010 (years)	Maximum cooling time thru 2010 (years)	Manu-facturer	Assay length (in.)
B1515B6	15×15	130	462.49	35247	49383	3.22	3.66	16.7	19.0	B&W	165.7
B1515B7	15×15	96	463.24	37204	48738	3.47	3.55	17.0	18.4	B&W	165.7
B1515B8	15×15	798	464.86	27124	54000	3.28	4.01	8.9	17.8	B&W	165.7
B1515B9	15×15	276	463.56	22796	53952	3.29	4.75	11.2	16.7	B&W	165.7
B1515BGD	15×15	4	429.55	45785	58310	3.91	3.92	22.0	23.3	B&W	165.7
B1515BZ	15×15	848	463.41	10000	54023	3.05	4.67	9.3	24.0	B&W	165.7
B1515W	15×15	8	461.82	25076	49075	3.9	4.21	11.3	17.3	WE	165.7
W1515A	15×15	889	428.88	20298	49859	2.01	3.6	11.3	31.7	ANF	159.8
W1515AHT	15×15	308	434.54	32682	56922	3.51	4.58	8.2	15.7	ANF	159.8
W1515APL	15×15	24	307.36	21470	37770	1.22	1.87	8.2	17.3	ANF	159.8
W1515W	15×15	393	451.19	12034	41806	2.21	3.34	25.0	34.8	WE	159.8
W1515WL	15×15	4644	455.23	8381	55385	1.85	3.8	13.8	37.8	WE	159.8
W1515WO	15×15	3576	460.76	5816	56138	1.91	4.59	8.7	25.7	WE	159.8
W1515WV5	15×15	531	457.79	14227	53056	2.98	4.79	8.2	15.3	WE	159.8
XHN15B	15×15	629	409.91	8193	37833	3	4.01	14.4	33.2	B&W	137.1
XHN15BZ	15×15	104	363.92	23813	42956	3.4	3.91	14.4	21.3	B&W	137.1
XHN15HS	15×15	1	406.16	32151	32151	3.98	3.98	35.6	35.6	Gulf	137.1
XHN15HZ	15×15	2	362.86	18546	18546	3.25	3.25	37.5	37.5	Gulf	137.1
XHN15MS	15×15	2	405.98	28324	28324	3.66	3.66	37.5	37.5	NU	137.1
XHN15MZ	15×15	2	370.77	25643	25643	2.95	2.95	37.5	37.5	NU	137.1
XHN15W	15×15	309	415.55	10742	35196	3.02	4	33.2	40.7	WE	137.1
XHN15WZ	15×15	53	384.89	8874	19376	4.2	4.6	14.4	14.4	WE	137.1
XPA15A	15×15	808	396.67	11837	51486	1.49	4.04	9.8	33.0	ANF	147.5
XPA15C	15×15	273	412.44	5139	33630	1.65	3.06	29.3	35.0	CE	147.5
XYR16A	15×16	228	233.56	22631	35088	3.49	4.02	23.7	32.2	ANF	111.8
XYR16C	15×16	156	228.77	6039	35999	3.51	3.92	19.2	22.1	CE	111.8

Table A-4 (continued)

Assembly code	Lattice	Number of assemblies	Average initial kgU	Minimum final assay average BU (MWd/MTU)	Maximum final assay average BU (MWd/MTU)	Minimum assay average initial enrichment (wt %)	Maximum assay average initial enrichment (wt %)	Minimum cooling time thru 2010 (years)	Maximum cooling time thru 2010 (years)	Manu-facturer	Assay length (in.)
XYR16U	15×16	73	238.57	4244	31986	3.96	4.02	33.6	36.6	UNC	111.8
C1616CSD	16×16	4080	414.01	11053	63328	1.86	4.63	8.6	29.8	CE	176.8
C8016C	16×16	2747	421.47	13902	56312	1.92	4.27	8.3	23.2	CE	178.3
XSL16C	16×16	909	381.02	9867	54838	1.71	4.28	9.1	26.2	CE	158.2
B1717B	17×17	4	456.72	25123	33904	2.64	3.03	29.0	30.8	B&W	165.7
W1717A	17×17	1210	413.84	20607	53958	2.43	4.77	8.3	24.8	ANF	159.8
W1717B	17×17	2060	455.80	5000	54014	2	4.6	8.3	19.3	B&W	159.8
W1717WL	17×17	10097	461.32	7227	58417	1.6	4.4	8.7	32.8	WE	159.8
W1717WO	17×17	3204	425.10	12030	53000	1.6	4.02	8.8	26.9	WE	159.8
W1717WP	17×17	216	417.07	44578	58237	3.73	4.81	8.7	13.2	WE	159.8
W1717WRF	17×17	72	455.49	42342	48037	3.99	4.41	8.2	10.3	WE	159.8
W1717WV	17×17	24	425.40	37862	48385	4.2	4.41	11.2	11.2	WE	159.8
W1717WV+	17×17	2126	424.01	21649	61685	1.61	4.65	8.2	16.3	WE	159.8
W1717WV5	17×17	4469	424.27	18865	56570	1.49	4.95	8.3	22.3	WE	159.8
W1717WVH	17×17	3868	461.95	11804	55496	2.11	4.95	8.2	19.9	WE	159.8
W1717WVJ	17×17	104	461.52	34132	46847	3.71	4.4	8.8	10.3	WE	159.8
WST17W	17×17	1254	540.48	10825	54399	1.5	4.41	8.2	21.4	WE	199
XYR18W	17×18	76	273.35	19054	31755	4.94	4.94	35.2	38.9	WE	111.8
G4806G10	6×6	11	178.57	5679	36591	3.06	4	8.7	11.8	GE	176.2
XDR06A	6×6	66	95.20	3241	5742	2.23	2.23	32.2	32.2	ANF	134.4
XDR06G	6×6	1	111	23522	23522	1.47	1.47	41.3	41.3	GE	134.4
XDR06G3B	6×6	163	101.61	9755	27106	1.82	1.83	33.5	41.3	GE	134.4
XDR06G3F	6×6	96	102.04	12387	28138	2.24	2.25	33.5	41.3	GE	134.4
XDR06G5	6×6	106	105.85	9065	25886	2.26	2.26	32.2	41.3	GE	134.4
XDR06U	6×6	458	102.02	4164	26396	1.83	2.26	32.2	41.3	UNC	134.4
XHB06A	6×6	126	69.73	1307	22377	2.35	2.41	34.5	35.6	ANF	95

Table A-4 (continued)

Assembly code	Lattice	Number of assemblies	Average initial kgU	Minimum final assay average BU (MWd/MTU)	Maximum final assay average BU (MWd/MTU)	Minimum assay average initial enrichment (wt %)	Maximum assay average initial enrichment (wt %)	Minimum cooling time thru 2010 (years)	Maximum cooling time thru 2010 (years)	Manu-facturer	Assay length (in.)
XHB06G	6×6	176	76.35	6119	22876	2.35	2.52	34.5	39.6	GE	95
G2307A	7×7	152	181.57	17663	27826	2.56	2.65	31.0	33.7	ANF	171.2
G2307G2A	7×7	1672	194.90	4493	24902	2.06	2.11	31.7	39.3	GE	171.2
G2307G2B	7×7	5047	193.20	177	29728	1.65	2.62	29.3	40.6	GE	171.2
G2307G3	7×7	395	187.42	5607	38861	1.96	2.6	26.7	35.3	GE	171.2
G4607G2	7×7	1142	194.72	959	11829	1.09	2.5	31.7	37.3	GE	176.2
G4607G3A	7×7	3752	187.45	2317	32188	1.1	2.51	25.1	35.6	GE	176.2
G4607G3B	7×7	1184	189.92	7695	30831	1.09	2.5	28.6	34.3	GE	176.2
XBR07G	7×7	4	131.50	1596	1690	2.88	2.88	42.5	42.5	GE	84
XDR07GS	7×7	1	59	29000	29000	3.1	3.1	41.3	41.3	GE	134.4
XHB07G2	7×7	88	76.33	15136	20770	2.08	2.31	37.3	39.6	GE	95
G2308A	8×8	1517	174.62	16205	36826	2.39	3.13	18.0	32.3	ANF	171.2
G2308AP	8×8	32	172.75	33686	34826	2.82	2.83	16.8	16.8	ANF	171.2
G2308G10	8×8	1404	172.22	5624	43977	3.1	3.55	8.2	15.2	GE	171.2
G2308G4	8×8	3944	183.99	16646	40523	2.19	2.75	23.2	32.2	GE	171.2
G2308G5	8×8	810	176.97	22519	33597	2.39	2.82	19.9	28.3	GE	171.2
G2308G7	8×8	164	178.52	29145	35894	2.96	2.99	15.9	15.9	GE	171.2
G2308G8A	8×8	1150	175.69	30074	44933	2.54	3.4	12.1	19.8	GE	171.2
G2308G8B	8×8	1382	172.36	21331	42518	2.95	3.39	10.2	17.9	GE	171.2
G2308G9	8×8	890	172.01	32167	42295	2.85	3.48	8.2	14.7	GE	171.2
G2308GB	8×8	1367	177.98	21943	43381	2.62	3.39	13.8	25.0	GE	171.2
G2308GP	8×8	3281	177.14	22466	38139	2.08	3.01	15.8	25.8	GE	171.2
G4608AP	8×8	1888	176.17	23000	35518	2.62	3.4	13.8	21.8	ANF	176.2
G4608G10	8×8	2337	177.77	18762	44343	2.63	3.7	8.7	17.8	GE	176.2
G4608G11	8×8	236	170.79	26390	42551	3.38	3.38	9.9	11.8	GE	176.2
G4608G12	8×8	88	180.87	13493	34462	3.69	3.99	9.9	11.8	GE	176.2

Table A-4 (continued)

Assembly code	Lattice	Number of assemblies	Average initial kgU	Minimum final assay average BU (MWd/MTU)	Maximum final assay average BU (MWd/MTU)	Minimum assay average initial enrichment (wt %)	Maximum assay average initial enrichment (wt %)	Minimum cooling time thru 2010 (years)	Maximum cooling time thru 2010 (years)	Manu-facturer	Assay length (in.)
G4608G4A	8×8	1785	183.93	5750	43430	2.19	2.99	18.8	33.4	GE	176.2
G4608G4B	8×8	1227	186.82	13379	32941	2.17	2.75	26.3	32.3	GE	176.2
G4608G5	8×8	4213	183.00	1829	38224	0.69	3.01	14.9	31.0	GE	176.2
G4608G8	8×8	3919	179.84	1969	44640	2.94	3.4	9.3	20.3	GE	176.2
G4608G8B	8×8	57	178.00	32647	38396	3.36	3.39	14.2	14.2	GE	176.2
G4608G9	8×8	7146	177.73	8722	47062	1.5	3.87	8.2	18.3	GE	176.2
G4608GB	8×8	10246	184.63	1814	45986	0.71	3.25	10.2	26.3	GE	176.2
G4608GP	8×8	12642	183.19	1676	42428	0.7	3.26	8.8	29.8	GE	176.2
G4608W	8×8	8	156.70	23000	33140	2.69	3.01	14.8	19.1	WE	176.2
XBR08G	8×8	2	112.5	2065	7027	2.85	2.85	41.7	42.5	GE	84
XDR08G	8×8	1	99.71	25287	25287	1.94	1.94	41.3	41.3	GE	134.4
9X9IXQFA	9×9	8	170.71	39079	39248	3.25	3.25	11.0	11.0	?	171.2
G2309A	9×9	1820	168.09	6210	40818	2.77	3.15	8.2	20.3	ANF	171.2
G2309AIX	9×9	224	169.18	11933	43778	3.25	3.81	8.2	9.2	ANF	171.2
G2309G11	9×9	132	165.65	31737	45117	3.1	3.78	9.2	13.8	GE	171.2
G4609A	9×9	3280	172.97	4000	47000	0.72	3.73	8.8	21.3	ANF	176.2
G4609A5	9×9	1124	176.15	28632	43555	2.9	3.55	9.7	17.3	ANF	176.2
G4609A9X	9×9	768	169.16	30682	43330	2.53	3.11	9.6	15.7	ANF	176.2
G4609AIX	9×9	12	174.79	16164	36777	3	3.93	8.2	17.3	ANF	176.2
G4609AX+	9×9	8	167.26	38043	40457	3.13	3.14	13.9	14.3	ANF	176.2
G4609G11	9×9	5351	170.12	5835	65149	1.46	4.14	8.3	16.9	GE	176.2
G4609G13	9×9	2060	171.41	11810	53636	3.23	4.17	8.2	14.8	GE	176.2
XBR09A	9×9	4	127.68	19061	22811	3.44	3.51	33.4	34.9	ANF	84
XBR09G	9×9	143	137.09	4802	22083	3.5	3.62	30.2	39.9	GE	84
ATRIUM10	10×10	128	176.90	37000	39000	3.94	3.94	9.8	9.8	ANP	176.2
G4610A	10×10	116	176.90	37000	39000	3.94	3.94	8.8	8.8	ANF	176.2

Table A-4 (continued)

Assembly code	Lattice	Number of assemblies	Average initial kgU	Minimum final assay average BU (MWd/MTU)	Maximum final assay average BU (MWd/MTU)	Minimum assay average initial enrichment (wt %)	Maximum assay average initial enrichment (wt %)	Minimum cooling time thru 2010 (years)	Maximum cooling time thru 2010 (years)	Manu-facturer	Assay length (in.)
G4610AIX	10×10	4	175.00	37412	38009	3.39	3.39	10.2	10.2	ANF	176.2
G4610C	10×10	148	175.68	17636	42640	2.51	3.62	9.6	14.8	ABB	176.2
G4610G12	10×10	371	176.09	36534	52735	3.12	4.2	8.2	10.3	GE	176.2
G4610G14	10×10	5	178.90	4365	38073	4.01	4.24	8.2	8.7	GE	176.2
XLC10A	10×10	178	108.6523	4678	20126	3.68	3.7	23.7	28.7	AC	102.5
XLC10L	10×10	156	120.1547 4	1591	21532	3.63	3.93	28.7	41.2	ANF	102.5
XBR11A	11×11	360	130.2331 7	3514	34212	3.13	3.82	13.3	31.9	ANF	84
XBR11G	11×11	6	124.5	20189	24997	3.11	3.63	38.8	38.8	GE	84
XBR11N	11×11	8	128.9875	15875	21850	2.16	3.5	33.4	36.6	NFS	84

Table A-5. Summary of UNF characteristics from which representative samples may be selected for PWR fuel assemblies [Ref. 5]

Assembly code	Number of assemblies	Initial uranium loading (kg/assembly)		Enrichment (U^{235} wt %)			Burnup (MWd/MTHM)		Cooling time thru 2010 (years)	
		Avg.	Max.	Min.	Avg.	Max.	Avg.	Max.	Min.	Max.
B1515B	103	463	465	2.74	3.57	3.62	40,407	50,128	8.2	14.2
B1515B10	681	477	489	3.24	3.9	4.73	44,417	56,880	8.2	15.2
B1515B3	181	464	466	1.08	2.42	2.84	21,036	32,267	16.7	32.8
B1515B4	4136	464	475	0.9	2.91	4.06	29,534	57,000	8.2	36.2
B1515B4Z	170	464	466	3.22	3.84	3.95	39,253	51,660	9.3	18.7
B1515B5	58	468	468	3.13	3.13	3.13	38,017	39,000	16.2	17.8
B1515B5Z	29	464	465	3.2	3.22	3.23	36,016	42,328	17.7	19
B1515B6	130	462	464	3.22	3.47	3.66	41,790	49,383	16.7	19
B1515B7	96	463	465	3.48	3.51	3.55	42,059	48,738	17	18.4
B1515B8	798	465	469	3.29	3.65	4.01	42,692	54,000	8.9	17.8
B1515B9	276	464	468	3.29	3.96	4.76	44,097	53,952	11.2	16.7
B1515BGD	4	430	430	3.92	3.92	3.92	49,027	58,310	22	23.3
B1515BZ	848	463	466	3.05	3.47	4.68	37,441	54,023	9.3	24
B1515W	8	462	465	3.9	4.06	4.22	36,993	49,075	11.3	17.3
B1717B	4	457	458	2.64	2.84	3.04	29,517	33,904	29	30.8
C1414A	1383	381	400	0.3	3.5	4.32	38,899	50,871	8.3	26.8
C1414C	4198	382	409	1.03	3.2	4.48	33,597	56,000	8.9	36.5
C1414W	552	403	412	2.7	3. 15	3.76	30,039	37,781	14.1	27.6
C1616CSD	4080	414	443	1.87	3.62	4.63	37,916	63,328	8.6	29.8
C8016C	2747	421	442	1.92	3.57	4.27	38,490	56,312	8.3	23.2
W1414A	1018	378	407	0.71	3.42	4.5	37,500	56,328	9.3	33.7
W1414ATR	288	363	368	2.39	3.38	3.57	38,168	46,000	18.9	26.3
W1414B	2	383	383	3.22	3.22	3.22	24,398	24,465	33.7	33.7
W1414W	603	394	404	2.26	3.04	3.47	27,315	39,723	24.8	39.9
W1414WL	1429	399	406	2.27	3.07	3.41	31,940	47,932	16.7	38.3
W1414WO	2108	356	369	0.99	3.92	4.95	44,730	69,452	8.1	27.8
W1515A	889	429	435	2.01	3	3.6	33,344	49,859	11.3	31.7
W1515AHT	308	435	438	3.51	4.08	4.59	45,441	56,922	8.2	15.7
W1515APL	24	307	310	1.23	1.55	1.88	27,971	37,770	8.2	17.3
W1515W	393	451	458	2.21	3	3.35	29,324	41,806	25	34.8
W1515WL	4644	455	466	1.85	2.98	3.8	30,874	55,385	13.8	37.8
W1515WO	3576	461	466	1.91	3.53	4.6	39,071	56,138	8.7	25.7

Table A-5 (continued)

Assembly code	Number of assemblies	Initial uranium loading (kg/assembly)		Enrichment (U^{235} wt %)			Burnup (MWd/MTHM)		Cooling time thru 2010 (years)	
		Avg.	Max.	Min.	Avg.	Max.	Avg.	Max.	Min.	Max.
W1515WV5	531	458	463	2.99	3.92	4.8	37,556	53,056	8.2	15.3
W1717A	1210	414	461	2.43	4.19	4.77	45,291	53,958	8.3	24.8
W1717B	2060	456	467	2	3.84	4.6	40,741	54,014	8.3	19.3
W1717WL	10097	461	469	1.6	3.12	4.4	32,340	58,417	8.7	32.8
W1717WO	3204	425	459	1.6	3.05	4.02	32,690	53,000	8.8	26.9
W1717WP	216	417	418	3.73	4.59	4.81	50,707	58,237	8.7	13.2
W1717WRF	72	455	457	4	4.18	4.42	45,530	48,037	8.2	10.3
W1717WV	24	425	426	4.21	4.38	4.41	44,263	48,385	11.2	11.2
W1717WV+	2126	424	465	1.61	4.16	4.66	45,430	61,685	8.2	16.3
W1717WV5	4469	424	431	1.49	4.01	4.95	43,872	56,570	8.3	22.3
W1717WVH	3868	462	474	2.11	3.87	4.95	41,081	55,496	8.2	19.9
W1717WVJ	104	462	465	3.71	3.99	4.4	43,922	46,847	8.8	10.3
WST17W	1254	540	547	1.51	3.38	4.41	35,926	54,399	8.2	21.4
XFC14A	192	353	359	3.5	3.57	3.8	37,205	46,048	18.9	26.8
XFC14C	418	362	377	1.39	2.96	3.95	32,130	52,125	9.8	35.9
XFC14W	229	374	376	0.27	3.75	4.25	38,521	51,971	8.7	14.2
XHN15B	629	410	415	3	3.99	4.02	33,776	37,833	14.4	33.2
XHN15BZ	104	364	368	3.4	3.8	3.91	34,278	42,956	14.4	21.3
XHN15HS	1	406	406	3.99	3.99	3.99	32,151	32,151	35.6	35.6
XHN15HZ	2	363	363	3.26	3.26	3.26	18,546	18,546	37.5	37.5
XHN15MS	2	406	407	3.66	3.66	3.66	28,324	28,324	37.5	37.5
XHN15MZ	2	371	371	2.95	2.95	2.95	25,643	25,643	37.5	37.5
XHN15W	309	416	421	3.02	3.59	4	27,922	35,196	33.2	40.7
XHN15WZ	53	385	387	4.2	4.39	4.6	14,321	19,376	14.4	14.4
XIP14W	160	191	200	2.83	4.12	4.36	16,471	27,048	36.2	38
XPA15A	808	397	408	1.5	3.17	4.05	34,362	51,486	9.8	33
XPA15C	273	412	417	1.65	2.47	3.06	16,020	33,630	29.3	35
XSL16C	909	381	394	1.72	3.44	4.28	38,807	54,838	9.1	26.2
XSO14W	657	368	375	3.16	3.87	4.02	27,232	39,275	18.1	40.2
XSO14WD	4	373	374	4.01	4.01	4.02	18,259	18,424	18.1	18.1
XSO14WM	4	311	311	0.71	0.71	0.71	19,307	19,636	37.6	37.6
XYR16A	228	234	237	3.49	3.78	4.02	29,034	35,088	23.7	32.2
XYR16C	156	229	233	3.51	3.8	3.92	24,282	35,999	19.2	22.1
XYR16U	73	239	241	3.96	3.99	4.02	27,461	31,986	33.6	36.6

Table A-5 (continued)

Assembly code	Number of assemblies	Initial uranium loading (kg/assembly)		Enrichment (U^{235} wt %)			Burnup (MWd/MTHM)		Cooling time thru 2010 (years)	
		Avg.	Max.	Min.	Avg.	Max.	Avg.	Max.	Min.	Max.
XYR18W	76	273	274	4.94	4.94	4.94	25,484	31,755	35.2	38.9

Table A-6. Summary of UNF characteristics from which representative samples may be selected for BWR fuel assemblies [Ref. 5]

Assembly code	Number of assemblies	Initial uranium loading (kg/assembly)		Enrichment (U^{235} wt %)			Burnup (MWd/MTHM)		Cooling time thru 2010 (years)	
		Avg.	Max.	Min.	Avg.	Max.	Avg.	Max.	Min.	Max.
9X9IXQFA	8	171	171	3.25	3.25	3.25	39166	39248	11	11
ATRIUM10	128	177	177	3.94	3.94	3.94	38406	39000	9.8	9.8
G2307A	152	182	184	2.56	2.64	2.65	24256	27826	31	33.7
G2307G2A	1672	195	198	2.07	2.1	2.11	16775	24902	31.7	39.3
G2307G2B	5047	193	197	1.65	2.15	2.62	16384	29728	29.3	40.6
G2307G3	395	187	189	1.96	2.41	2.6	25420	38861	26.7	35.3
G2308A	1517	175	184	2.39	2.66	3.13	28814	36826	18	32.3
G2308AP	32	173	173	2.82	2.83	2.83	34366	34826	16.8	16.8
G2308G10	1404	172	174	3.1	3.25	3.56	33988	43977	8.2	15.2
G2308G4	3944	184	185	2.19	2.51	2.76	26087	40523	23.2	32.2
G2308G5	810	177	178	2.39	2.66	2.82	29009	33597	19.9	28.3
G2308G7	164	179	179	2.96	2.97	2.99	31570	35894	15.9	15.9
G2308G8A	1150	176	180	2.55	3.09	3.4	34848	44933	12.1	19.8
G2308G8B	1382	173	178	2.96	3.19	3.39	36400	42518	10.2	17.9
G2308G9	890	172	173	2.85	3.18	3.48	37268	42295	8.2	14.7
G2308GB	1367	178	180	2.62	2.8	3.39	32014	43381	13.8	25
G2308GP	3281	177	179	2.08	2.77	3.01	29317	38139	15.8	25.8
G2309A	1820	168	170	2.78	3.1	3.15	35941	40818	8.2	20.3
G2309AIX	224	169	170	3.25	3.31	3.82	39151	43778	8.2	9.2
G2309G11	132	166	170	3.1	3.56	3.78	40522	45117	9.2	13.8
G4607G2	1142	195	197	1.09	1.56	2.5	9362	11829	31.7	37.3
G4607G3A	3752	187	189	1.1	2.33	2.51	21058	32188	25.1	35.6
G4607G3B	1184	190	192	1.1	2.31	2.51	21948	30831	28.6	34.3
G4608AP	1888	176	177	2.62	2.88	3.4	31248	35518	13.8	21.8
G4608G10	2337	178	186	2.63	3.24	3.7	36695	44343	8.7	17.8
G4608G11	236	171	171	3.38	3.38	3.38	35194	42551	9.9	11.8
G4608G12	88	181	181	3.69	3.71	3.99	32069	34462	9.9	11.8
G4608G4A	1785	184	185	2.19	2.62	2.99	24931	43430	18.8	33.4
G4608G4B	560	187	188	2.1	2.31	2.76	21362	32941	25.8	32
G4608G5	4213	183	185	0.7	2.36	3.01	23964	38224	14.9	31
G4608G8	3919	180	186	2.95	3.19	3.4	34905	44640	9.3	20.3
G4608G9	7146	178	186	1.51	3.23	3.88	36492	47062	8.2	18.3
G4608GB	10246	185	187	0.71	2.53	3.25	26297	45986	10.2	26.3
G4608GP	12642	183	187	0.7	2.38	3.27	23112	42428	8.8	29.8
G4608W	8	157	171	2.69	2.85	3.01	28041	33140	14.8	19.1
G4609A	3280	173	175	0.72	3.42	3.73	36933	47000	8.8	21.3
G4609A5	1124	176	177	2.9	3.28	3.55	36536	43555	9.7	17.3
G4609A9X	768	169	177	2.53	2.87	3.11	36880	43330	9.6	15.7
G4609AIX	12	175	177	3	3.58	3.94	24156	36777	8.2	17.3
G4609AX+	8	167	167	3.13	3.14	3.15	39239	40457	13.9	14.3
G4609G11	5351	170	178	1.46	3.56	4.14	40351	65149	8.3	16.9
G4609G13	2060	171	173	3.24	3.85	4.17	42045	53636	8.2	14.8
G4610A	116	177	177	3.94	3.94	3.94	38207	39000	8.8	8.8
G4610AIX	4	175	175	3.39	3.39	3.39	37706	38009	10.2	10.2
G4610C	148	176	176	2.51	3.29	3.62	38133	42640	9.6	14.8
G4610G12	371	176	182	3.12	3.98	4.2	44175	52735	8.2	10.3

Table A-6 (continued)

Assembly code	Number of assemblies	Initial uranium loading (kg/assembly)		Enrichment (U^{235} wt %)			Burnup (MWd/MTHM)		Cooling time thru 2010 (years)	
		Avg.	Max.	Min.	Avg.	Max.	Avg.	Max.	Min.	Max.
G4610G14	5	179	180	4.01	4.11	4.24	5868	8915	8.2	8.7
XBR07G	4	132	133	2.88	2.88	2.88	1643	1690	42.5	42.5
XBR08G	2	113	113	2.85	2.85	2.85	4546	7027	41.7	42.5
XBR09A	4	128	131	3.45	3.48	3.52	20981	22811	33.4	34.9
XBR09G	143	137	141	3.51	3.58	3.62	15092	22083	30.2	39.9
XBR11A	360	130	133	3.13	3.42	3.82	22716	34212	13.3	31.9
XBR11G	6	125	132	3.11	3.46	3.63	22802	24997	38.8	38.8
XBR11N	8	129	134	2.16	2.83	3.51	18940	21850	33.4	36.6
XDR06A	66	95	95	2.23	2.23	2.24	4907	5742	32.2	32.2
XDR06G	1	111	111	1.47	1.47	1.47	23522	23522	41.3	41.3
XDR06G3B	163	102	103	1.83	1.83	1.83	18632	27106	33.5	41.3
XDR06G3F	96	102	103	2.25	2.25	2.25	22132	28138	33.5	41.3
XDR06G5	106	106	112	2.26	2.26	2.26	21095	25886	32.2	41.3
XDR06U	458	102	103	1.83	2.24	2.26	17685	26396	32.2	41.3
XDR07GS	1	59	59	3.1	3.1	3.1	29000	29000	41.3	41.3
XDR08G	1	100	100	1.95	1.95	1.95	25287	25287	41.3	41.3
XHB06A	126	70	74	2.35	2.4	2.41	9037	22377	34.5	35.6
XHB06G	176	76	77	2.35	2.43	2.52	17170	22876	34.5	39.6
XHB07G2	88	76	77	2.08	2.11	2.31	18187	20770	37.3	39.6
XLC10A	178	109	110	3.68	3.69	3.71	15017	20126	23.7	28.7
XLC10L	156	120	121	3.63	3.77	3.94	14419	21532	28.7	41.2

APPENDIX B

DOE-OWNED USED NUCLEAR FUEL CHARACTERISTICS

Table B-1. Ranges of nominal properties for DOE-owned used nuclear fuel [Ref. 3]

Fuel group	MTHM[a]	EOL effective enrichment (%)	Cladding composition	Cladding condition	Fuel compound names	Fuel matrix	Configuration	Length (ft)	Width/ height/ diameter (in.)
01. U metal, zirc clad, LEU	2103	1.7–0.5	Zirconium	Fair Poor	U metal	None	Plates Tubes	2.1–9.9	1.0–4.3
02. U metal, nonzirc clad, LEU	8	3.4–0.2	SST Aluminum	Poor Good Fair	U metal	None	Cans of scrap Tubes None	0.6–0.9	1.4–1.9
03. U-zirc	<1	92.9–0.5	Zirconium	Fair Good	U metal 2% Zr U-Zr	None	Tube Cylinders Plates	2.0–12.5	2.0–7.4
04. U-Mo	4	25.8–2.4	Zirconium Aluminum None	Good Poor Fair None	U-Mo	None	Rod Tube Plates in can	1.0–3.8	0.1–2.1
05. U oxide, zirc clad, intact, HEU	<1	92.5–23.1	Zirconium	Fair Good	UO_2	ZrO_2-CaO Graphite ZrO_2	Rod Assembly Plates	3.1–9.0	0.3–7.4
06. U oxide, zirc clad, intact, MEU	2	6.9–5	Zirconium	Fair Good	UO_2	None	Plates Rod Cans of rods Element	2.9–5.2	0.3–3.8
07. U oxide, zirc clad, intact, LEU	90	4.9%–0.6	Zirconium	Good Fair	UO_2	None	Tubes Rod Plates Assembly	0.8–14.7	0.4–8.5
08. U oxide, SST/hastelloy clad, intact, HEU	<1	93.2–91.0	SST Hastelloy	Good Fair	U oxide UO_2	SST SST (316L) SST 304B SST 304 None	Tubes Cans of scrap Rod Plates Rod assembly	2.1–6.6	0.9–3.7
09. U oxide, SST clad, intact, MEU	<1	20.0–5.5	SST	Good Fair	UO_2-BeO_2 UO_2	ZrO_2-CaO None	Rod Element	2.4–4.0	0.3–1.5
10. U oxide, SST clad, intact, LEU	<1	1.9–0.2	SST	Good Fair	UO_2	None	Tube Rod	1.5–12.0	0.4–8.5

Table B-1 (continued)

Fuel group	MTHM[a]	EOL effective enrichment (%)	Cladding composition	Cladding condition	Fuel compound names	Fuel matrix	Configuration	Length (ft)	Width/ height/ diameter (in.)
11. U oxide, nonalum clad, nonintact or declad, HEU	<1	93.3–21.0	Nichrome Hastelloy SST Zirconium None	Poor None	UO_2	BEO SST Nichrome None	Cans of scrap	0.2–2.8	2.8–5.6
12. U oxide, nonalum clad, nonintact or declad, MEU	<1	18.6–5.2	None Zirconium SST	Poor	UO_2	Gd_2O_3 None SST	Experiment capsule Scrap Cans of scrap	3.4–9.9	0.4–9.1
13. U oxide, nonalum clad, nonintact or declad, LEU	83	3.2–1.1	Zirconium SST	Poor	UO_2	None	Cans of scrap Scrap Rod	12.4–13.5	0.5–14.0
14. U oxide, alum clad, HEU	5	89.9–58.1	Aluminum	Good Fair	U_3O_8	Alum	Plates	2.0–3.6	2.8–17.2
15. U oxide, alum clad, MEU and LEU	<1	20.0–8. 9	Aluminum	Good Fair	U_3O_8	Alum	Plates Assembly	2.2–3.3	3.0–4.8
16. U-ALx, HEU	8	93.3–21.9	Aluminum	Good Fair	U-ALx	Alum	Rods Tubes Plates Pin cluster Assemblies Elements	0.4–10.1	1.3–16.3
17. U-ALx, MEU	3	20.0–9.0	Aluminum	Good Fair	U-ALX	Alum	Assembly Element Plates	2.0–3.4	2.1–4.1
18. U3Si2	8	22.0–5.2	Aluminum	Good Fair Poor	U_3SI_2	Alum	Tubes Multi-pin cluster Assembly Cans of Scrap	2.0–3.4	2.6–4.1
19. Th/U carbide, TRISO or BISO coated particles in graphite[b]	25	84.4–71.4	BISC TRISO	Good	ThC_2-UC_2 ThC-UC	Graphite	Tubes Cans of scrap	2.6–10.5	3.5–14.2

Table B-1 (continued)

Fuel group	MTHM[a]	EOL effective enrichment (%)	Cladding composition	Cladding condition	Fuel compound names	Fuel matrix	Configuration	Length (ft)	Width/ height/ diameter (in.)
20. Th/U carbide, mono-pyrolytic carbon coated particles in graphite[b]	2	93.2–80.6	Mono-pyrolytic carbon	Poor	ThCO-UCO ThC_2-UC_2	Graphite	Element Carbon coated part Cans of Scrap	~12.0	~3.5
21. Pu/U carbide, nongraphite clad, not sodium bonded	<1	67.3–1	SST	Good Fair Poor	Pu/U carbide	None	Element Cans of scrap Rod	7.7–12.0	0.2–5.2
22. MOX, zirc clad	2	21.3–1.3	Zirconium	Poor Good Fair	PuO_2-UO_2	None	Rod Cans of Scrap Plates Element	3.3–7.1	0.3–6.6
23. MOX, SST clad	11	87.4–2.1	SST	Poor Good Fair	PuO_2-UO_2 PuO_2	None	Rod Plates Element Cans of Scrap Scrap	1.1–12.0	0.2–9.1
24. MOX, non-SST/nonzirc clad	<1	54.3–5	Unknown	N/A Poor	PuO_2-UO_2	None Unknown	Scrap Cans of scrap	Unknown	Unknown
25. Th/U oxide, zirc clad	43	98.4–10.1	Zirconium	Good Poor N/A	ThO_2-UO_2 ceramic	None	Rod Assembly Cans of scrap	~11.8	9.0–22.3
26. Th/U oxide, SST clad	8	97.8–7.6	SST	Fair Good Poor	ThO_2-UO_2	None	Assembly Cans of scrap Rod	5.2–11.7	0.4–11.9
27. U-zirc hydride, SST/incoloy clad, HEU	<1	93.2–42.5	SST Incoloy	Good Fair	U-ZrHX-Er	None	Rod Element	2.4–3.8	0.5–3.2
28. U-zirc hydride, SST/incoloy clad, MEU	2	20.0–11.9	SST Incoloy	Good Poor	U-ZrHX U-ZrHX-Er	None	Element Canister of scrap	2.4–3.8	~1.5
29. U-zirc hydride, alum clad, MEU	<1	20.0–16.8	Aluminum	Good	U-ZrHX	None	Element	~2.4	~1.5
30. U-zirc hydride, declad	<1	~89.7	None	N/A	U-ZrHX	None	Declad rod	~1.2	~1.2

Table B-1 (continued)

Fuel group	MTHM[a]	EOL effective enrichment (%)	Cladding composition	Cladding condition	Fuel compound names	Fuel matrix	Configuration	Length (ft)	Width/ height/ diameter (in.)
31. Metallic sodium bonded	60	93.2-<0.1	SST None Unknown	Poor Good N/A Fair	PuO_2-UO_2 U-10Zr U-Mo U-10Zr U metal U-Pu-Zr UO_2 U metal Pu/U alloy U-5 fissium Pu/U carbide	None	Fuel in sodium Rod Assembly Cans of Scrap Scrap	1.8–12.0	0.2–9.1
32. Naval	65	—	—	—	—	—	—	—	—
33. Canyon stabilization	N/A	—	—	—	—	—	—	—	—
34. Misc (not previously listed)	<1	90.0–14.6	None Zirconium Unknown Aluminum SST	Fair Poor N/A Good	ThO_2-UO_2 U-Th metal U metal Am oxide Pu/U nitride	None Alum (1100) Unknown	Cans of scrap Tube Rod	0.3–9.9	0.5–2.6

[a]MTHM are rounded to next higher whole number or reported as <1 MTHM, as applicable.
[b]For fuel groups 19 and 20, cladding composition and cladding condition are reporting particle coating composition and condition.
Group 31 is sodium-bonded fuel. Some of this material has been or will be treated into HLW.
Group 33 will be processed into HLW.