# Categorization of Used Nuclear Fuel Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy - 13575[a]

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## ABSTRACT

A technical assessment of the current inventory [~70,150 metric tons of heavy metal (MTHM) as of 2011] of U.S.-discharged used nuclear fuel (UNF) has been performed to support decisions regarding fuel cycle strategies and research, development and demonstration (RD&D) needs. The assessment considered discharged UNF from commercial nuclear electricity generation and defense and research programs and determined that the current UNF inventory can be divided 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/reactors); and
3. Recycle/Recovery – material with inherent and/or strategic value.

A set of key assumptions and attributes relative to the various disposition options were used to categorize the current UNF inventory. Based on consideration of RD&D needs, time frames and material needs for deployment of alternative fuel cycles, characteristics of the current UNF inventory, and possible uses to support national security interests, it was determined that the vast majority of the current UNF inventory should be placed in the Disposal category, without the need to make fuel retrievable from disposal for reuse or research purposes. Access to the material in the Research and Recycle/Recovery categories should be retained to support RD&D needs and national security interests. 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.

## INTRODUCTION

This paper summarizes a recent technical assessment of the current inventory of U.S. domestic-discharged used nuclear fuel (UNF) in support of a comprehensive national nuclear fuel cycle strategy.[1]

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The assessment was performed for the Department of Energy Office of Nuclear Energy's (DOE-NE) Fuel Cycle Technologies (FCT) program and is intended to support near-term and future decisions regarding fuel cycle strategies and research, development and demonstration (RD&D) needs. The objective of the 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 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 needed for a future use such as 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 fuel 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 metric tons of heavy metal (MTHM)] and diversity of the domestic UNF inventory and the fact that U.S. commercial nuclear power plants are discharging ~2,000 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 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 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 ~2,000 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.[2]

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.

A description of the assessment of the UNF relative to retention needs, criteria for UNF categorization, and results of the categorization are discussed below.

## OVERVIEW OF U.S. USED NUCLEAR FUEL INVENTORY

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,[3] ~2,500 MTHM of DOE-owned UNF, and ~50 MTHM of highly enriched uranium (HEU) UNF that is greater than 90 wt % $^{235}U$ are currently stored at 79 sites in 34 states.[4, 5] 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 [6] 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,[a] 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. 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.[7] However, these proportions will slowly change [7, 8] 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 Fig. 1.

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

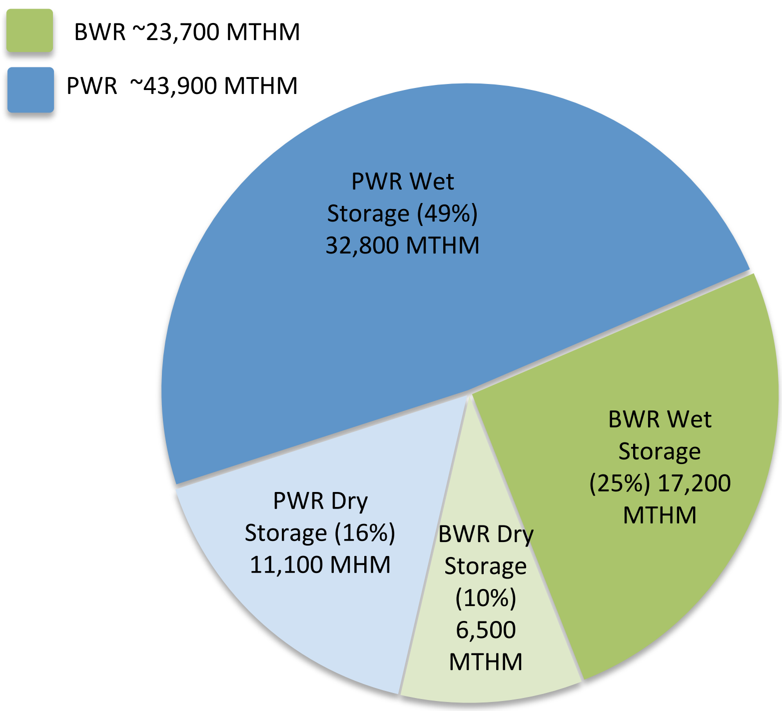


Fig. 1. Distribution of current (2011) commercial UNF inventory from PWRs and BWRs in wet and dry storage (data from Refs. 3, 6, 7, 9).

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 small 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 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 [6] by physical configuration into 22 classes: 16 PWR and 6 BWR fuel assembly classes, as shown in Fig. 2. Within an assembly class, assembly types are of a similar size. There are 137 individual fuel assembly types in these 22 classes. 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 have cost and operating implications for recycling (e.g., designing and operating a recycling facility and associated processes that can accommodate such wide variations in feedstock).

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, assembly-average enrichment has increased across the U.S. commercial reactor fleet and is approaching the current limit of 5 wt % $^{235}U$, and burnup values have been increasing and will ultimately be limited by the limit on initial fuel enrichments.[a] Further, the variation in assembly classes is decreasing as a number of fuel types, particularly reactor-specific fuel types, have been discontinued. Looking forward, less variability in the characteristics of discharged UNF assemblies is expected, resulting in more a uniform source of feedstock for potential future reprocessing.

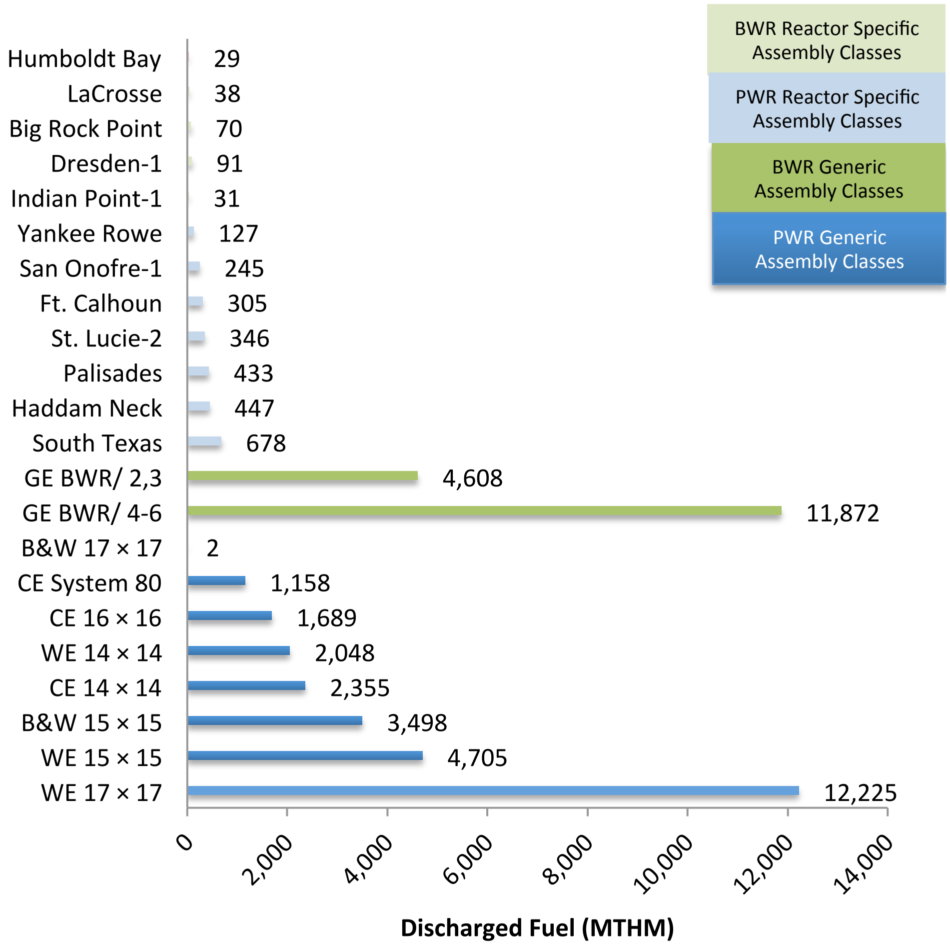


Fig. 2. Distribution of assembly classes by total mass in the commercial UNF inventory as of 2002. *Source*: Ref. 6.

## ASSESSMENT OF THE UNF RELATIVE TO RETENTION NEEDS

Execution of the DOE-NE's FCT mission requires access to select UNF material to support program objectives pertaining to UNF management and alternative fuel cycles, and hence the potential needs for access to UNF material are discussed in terms of those two applications in this section.

[a]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.

## Used Nuclear Fuel Management

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 UFDC completed a technical gap analysis for extended storage [10] in January 2012 and for transportation [11] in August 2011. Both efforts, as well as similar efforts by the Nuclear Regulatory Commission (NRC),[12] the Electric Power Research Institute (EPRI),[13] and the Nuclear Waste Technical Review Board (NWTRB),[14] identified data and modeling needs and proposed RD&D activities for the identified gaps. Access to a representative sample, as well as sufficient quantities to enable reliable statistical analyses, of the diverse commercial UNF inventory is needed to support phenomenological/separate effects, small-scale, and full-scale demonstration testing required to close these technical gaps.[15] 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.

With this objective in mind, a review of the U.S. UNF inventory and previous similar efforts [16] 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 cladding integrity and 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 operating history.

### Assembly Design

As of the end of 2011, an estimated ~234,000 commercial fuel assemblies containing 67,600 MTHM have been discharged.[3] BWR used fuel assemblies are arranged in 6×6, 7×7, 8×8, 9×9, 10×10, and 11×11 arrays of fuel pins. PWR used fuel assemblies are 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. [6] 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.

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 type manufactured by each of the vendors, including variations in fuel rod clad, grid, and assembly hardware materials used.

### Assembly Operating History

For the selection criteria used for assembly operating history, a range of the following parameters is desired for retention to support RD&D.

- **Assembly Burnup:** As all phenomena relevant to UNF storage, transportation, and disposal are directly or indirectly related to fuel burnup, sufficient 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.[17] 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.
- **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.
- **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 burnable poison and control rods, 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.[7] The remainder (~74%) is stored (wet) in spent fuel pools. Some of the dry storage casks were loaded more than 15 years ago. 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.
- **Post-Irradiation Assembly Condition:** Selection of UNF for retention should 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,[6] 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, $1.32 \times 10^{-5}$ by mass through 2002,[6] of the UNF has been disassembled and the removed fuel rods placed into consolidated fuel canisters.[18] Retained UNF should consider inclusion of consolidated fuel to support resolution of potential future issues that may arise.

## Alternative Fuel Cycles

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.

Depending on the outcome of RD&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 time frame for deployment of these fuel cycles.

The current U.S. fleet of 104 operating reactors discharges ~2,000 MTHM of UNF annually. The current inventory of commercial UNF, ~67,600 MTHM, is the result of reactor operation over the last ~50 years. 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 Fig. 3, 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 ~1,700 MTHM for disposal. For UNF generated in subsequent decades, the figure identifies the material for disposal and retention assuming a constant discharge rate of 2,000 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. 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.

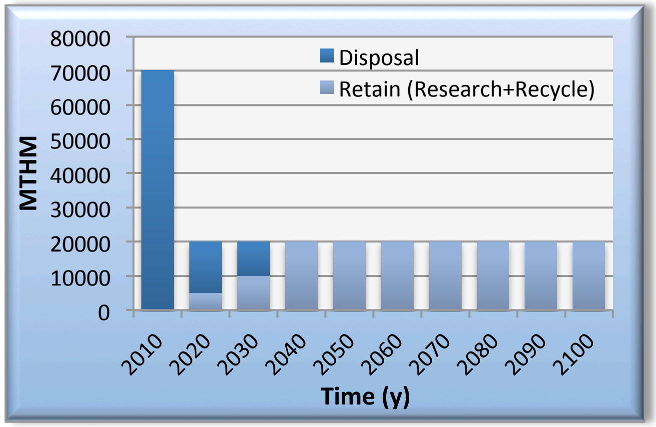


Fig. 3. Categorization of UNF assuming current discharge rate and recycling beginning in 2030.

It is noted, however, that a potential exception to the above conclusion is the case where a rapid deployment of certain fuel cycles would be anticipated. There are fuel cycles [19] 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 very 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 ~1,000 MTHM of used LWR fuel. With ~2,000 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 UNF stockpiles, as well as rapid deployment of reprocessing that significantly exceeds a production rate of 2,000 MTHM per year, would be necessary (or enriched uranium would have to be substituted for plutonium start-up fuel).

To fully understand the potential material needs for deployment of fast reactors, several specific scenarios and the sensitivity of the material needs to the various scenario assumptions were evaluated. As a 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,[20] 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 reactors that are constructed to address the electricity growth requirements and to replace the retirement of the LWR fleet after 2050 are assumed to be fast reactors; until that time new LWRs are deployed. This scenario, depicted in Fig. 4, would require reprocessing of LWR UNF to begin several years prior to the first fast reactor coming online to develop sufficient material for reactor startup. Even in this scenario it is demonstrated that there is sufficient plutonium available in the LWR UNF discharged from 2020 onwards to fuel all of the future fast reactors as they reach equilibrium with self-sustaining plutonium recycle.

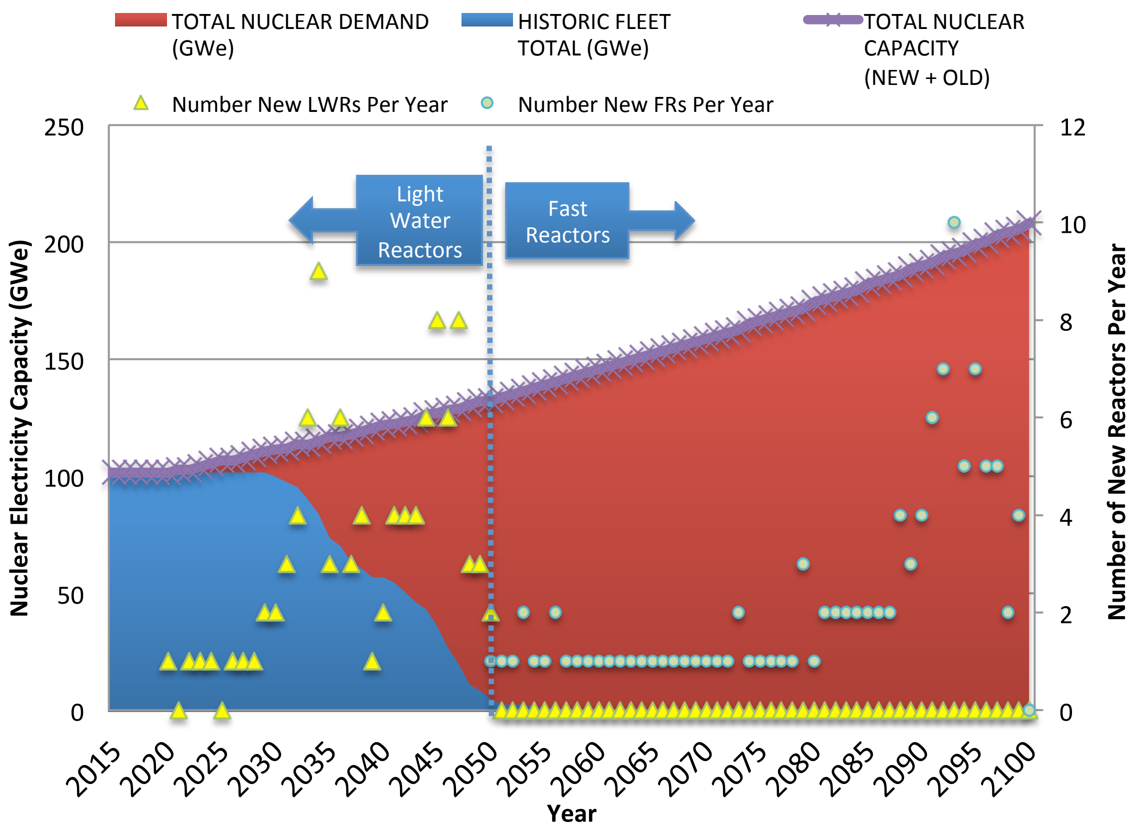


Fig. 4. Example scenario in which fast reactors take on a prominent role in the potential growth of nuclear electricity. *Source*: Ref. 21.

While several of the example fast-reactor deployment scenarios considered are in contradiction with several of our key assumptions, the conclusion that the existing inventory of LWR UNF is not needed remains valid.

## USED NUCLEAR FUEL CATEGORIES

Based on the assessment of UNF relative to retention needs discussed previously, it is proposed that the current UNF inventory can be divided into the following three categories.

- **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 [22] 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 is based on the observation that value must exceed cost, or liability, for a potential resource to be used.

- **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.

- **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 or for other purposes. This category includes commercial UNF for recycle to commercial systems as well as recovery of strategic materials, such as HEU. For any material placed in this category, it is judged that access to that material should be preserved for recycling or recovery purposes.

## 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: disposal, research, recycle/recovery.

### 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.

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 ~2,500 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.

### Research

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. 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 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 above. 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,[10] 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 for research purposes. 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, for high-capacity rail casks, the high end of the range (i.e., ~1,150 MTHM) may be necessary if candidate casks must be selected from already-loaded casks and if it is decided that access to some of each of the reactor-specific assembly types must be retained. 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 amount of material for which access is retained. Therefore, based on this assessment, it is suggested that access to up to ~1,150 MTHM (see Ref. [1] for more details) of the current commercial UNF be retained to support UNF management RD&D.

As was discussed, there is also 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 ~2,000 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, it may be decided in the future that the current commercial UNF for which access is retained to support advance fuel cycle RD&D should be replaced at appropriate intervals with future discharged UNF.

### Recycle/Recovery

It is not anticipated that any of the current inventory of UNF would be needed to support deployment of a future 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 [23] 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. However, there is up to ~50 MTHM of HEU UNF that has potential usefulness to support national interests. This material represents U.S.-origin enriched uranium that is not subject to international consent agreements. Given the special nature of this material, it is recommended that up to ~50 MTHM of this material be retained for possible future recovery.

### Summary

The results of the categorization discussed in the above sections are summarized in Table I. The estimated total amount in the Research category (~1,646 MTHM) includes ~1146 MTHM to support UNF management RD&D and ~500 MTHM to support alternative fuel cycles RD&D, and represents ~2% (by mass) of the total UNF inventory.

TABLE I. 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 |

## CONCLUSIONS

A technical assessment was conducted for 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, naval, 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 ~1,700 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 ~2,000 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.

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.

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