Prioritization Criteria for the Selection of Used Nuclear Fuel for Recycling - 11008

W. Mark Nutt*, Zachary Duncan**, Thomas Cotton ***
*Argonne National Laboratory
**University of Illinois
***Complex Systems Group LLC

ABSTRACT

As of April 2005, the U.S. nuclear fleet had generated approximately 50,000 metric tons of used nuclear fuel that is being stored either in spent fuel pools or in dry storage systems. The burn-up of this used fuel ranges from less than 10 GWd/MT to over 60 GWd/MT, with a median around 40 GWd/MT. Some of this fuel has resided in storage for upwards of 40 years. The U.S. nuclear fleet currently discharges approximately 2,000 metric tons per year and increasing the use of nuclear power to meet electricity generation needs would lead to a proportional increase in the annual discharge rate. The nuclear industry has continually increased the discharge burn-up towards 60 GWd/MT, with the potential to irradiate fuels to higher burn-up fuel being explored.

The U.S. is currently exploring alternatives for managing used nuclear fuel and recycling it is under active consideration. While all used fuel could theoretically be recycled, there is a question of practicality regarding whether the entire inventory of used fuel would and could be recycled. The decision to pursue a closed fuel cycle and the type of fuel cycle that could be deployed would depend on many technical, social, and political factors.

This paper does not explore these factors, but rather discusses criteria that could potentially influence decisions regarding priority of used fuel that would be recycled, ranging from low burn-up, long-cooled fuel stored in sealed dry canisters to high burn-up, short-cooled fuel stored in reactor pools. The criteria evaluated fall into three broad categories: subsequent re-use in a reactor, design/operation of a separations plant, and waste management. This paper does not consider or assume a single recycling technique, rather it investigates the general criteria that would likely be considered in determining the characteristics of the fuel that would be reprocessed.

INTRODUCTION

The U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) recently developed a roadmap of its research, development and demonstration (RD&D)activities that will ensure nuclear energy remains a compelling and viable energy option for the United States [Ref. 1]. One of the four RD&D objectives to address the challenges to expanding the use of nuclear power is the development of sustainable nuclear fuel cycles.

The DOE-NE is investigating three strategies that may be deployed in the future and develop technologies that could demonstrate the best approach within each of these strategies [Ref. 2]:

- **Once-Through Fuel Cycle** – 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 strategy 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 fuel processing technologies, perhaps including separation, 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 improve waste management characteristics.

- **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) would be disposed, not used fuel. Implementing this system will require extensive use of separation technologies.

Once the RD&D is sufficiently advanced, perhaps twenty or thirty years from now, decision-makers will have sufficient information to decide which of the approaches are best suited for demonstration. As a target, the DOE-NE RD&D effort is guided by the goal of enabling a national decision to deploy a chosen fuel cycle system by 2050.

It is clear that the current once-through fuel cycle will continue for at least the next 40 years, generating used nuclear fuel that will need to be managed. Depending on the growth[1] of nuclear power, it has been estimated that ~140,000 – ~235,000 metric tons uranium (MT) of used light water reactor (LWR) nuclear fuel (~480,000 – ~800,000 fuel assemblies) will have been generated by 2050 [Ref. 3]. Annual used LWR nuclear fuel discharge rates have been estimated to range from ~2,000 to ~9,000 MT per year at 2050 for different growth scenarios where nuclear power would continue to contribute to U.S. energy generation [Ref. 3].

While the entire inventory of discharged nuclear fuel could potentially be recycled either in a modified open or a full recycle fuel cycle, two practical considerations must be taken into account. First, it is unlikely that the U.S. would deploy sufficient capacity to recycle the entire inventory of discharged LWR (separations plants, fabrication plants, and reactors capable of irradiating the recycled fuel) should one of these fuel cycles be selected. Second, there is likely to be a transition phase between the current once-through fuel cycle utilizing LWRs to an advanced fuel cycle. It is therefore likely that some of the discharged used nuclear fuel would be deemed as spent nuclear fuel (no value to recycle) to be disposed of in a geologic repository. This would result in a combination of the current once-through fuel cycle and a future advanced sustainable fuel cycle being implemented.

A variety of criteria would potentially be considered in selecting the discharged LWR fuels that would be chosen for recycling in an advanced fuel cycle. Several of these criteria, and their impacts, are discussed herein.

APPLICABLE CHARACTERISTICS OF USED NUCLEAR FUEL

The criteria that would potentially be used are strongly dependent on the characteristics of the discharged LWR fuel and as such, the input conditions must first be determined. The three major characteristics that would play the most significant role are functions of the residence time of the discharged fuel in a reactor (the burn-up) and the time between discharge and subsequent recyling (storage time) and are:

- Fissile isotope inventory;
- Transuranic and fission product isotope inventory; and
- Heat generation rate.

[1] Carter and Luptak [Ref. 3] considered four different growth scenarios in forecasting the inventory of used nuclear fuel that would be generated: 1) a phase out of the existing fleet, 2) maintain the current nuclear generation at ~ 100 GWe/year, 3) growth to ~ 200 GWe/year by 2060, and 4) growth to ~ 400 GWe/year by 2060

These characteristics (parameters) have been quantified for commercial PWR and BWR nuclear fuel as a function of discharge burn-up and time after discharge using mass balances developed to estimate the quantity of potential advanced nuclear fuel cycle waste forms [Ref. 3]. Figure 1 shows the historical and projected average discharge burn-up of PWR and BWR fuel. Discharge burn-up has historically increased and is expected to continue to do so in the future, approaching 55 GWd/MT by 2020. The lowest burn-up fuel assemblies, by nature of when they were discharged, will have spent the longest time in storage. Higher burn-up fuel assemblies will have spent less time in storage. Much of the lower burn-up, longer cooled fuel has been placed in dry storage. The number of assemblies, and their burn-up, that will be placed in dry storage will increase as fuel assemblies are discharged and spent fuel pool capacities are approached.

Table I shows the mass of U-235 and U-238 along with the U-235 weight fraction in LWR fuel as a function of discharge burn-up. It can be seen that there is very little, if any change in the mass of U-235 in the discharge fuel between low and moderate burn-up. However, there is a significant decrease in the U-235 concentration as the burn-up increases to high levels (60 GWd/MT for PWR fuel and 50 GWd/MT for BWR fuel).

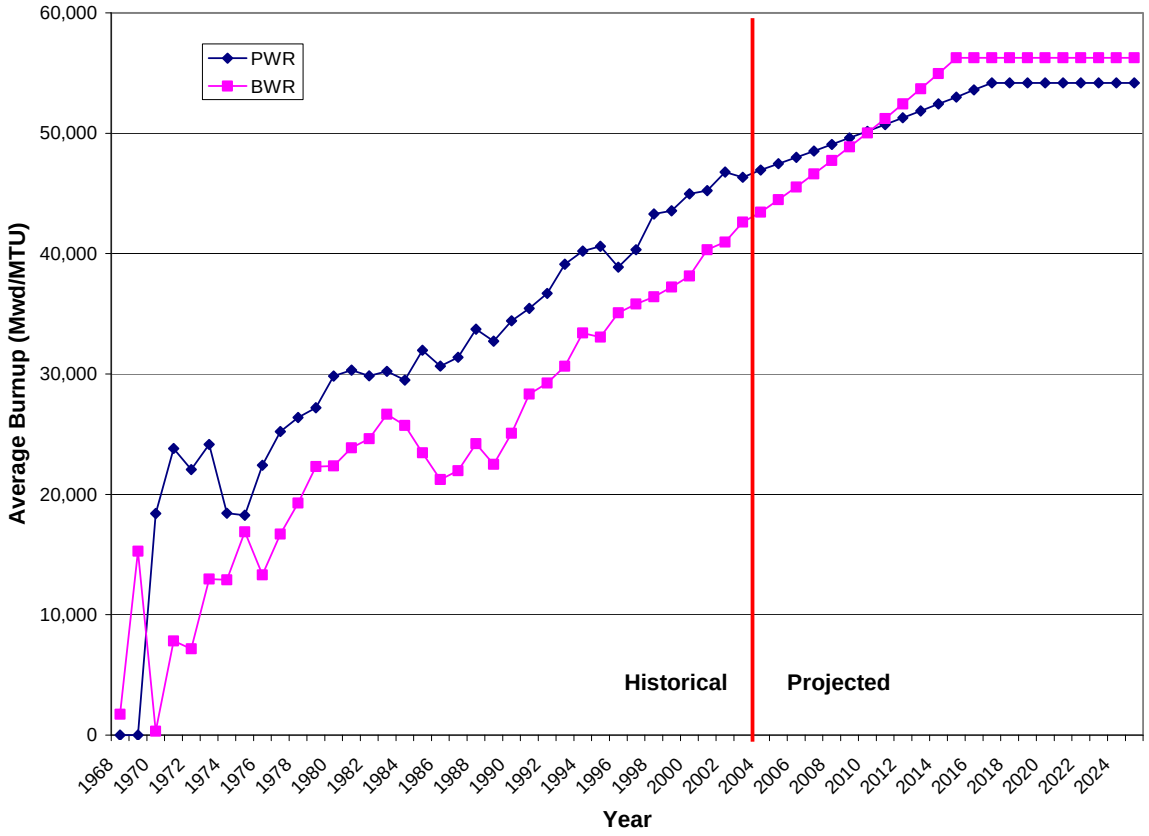

Fig. 1. Average burn-up of discharge LWR fuel assemblies [from Ref. 1]

Table I. Uranium isotopic inventory in discharge LWR fuel [from Ref. 3]

Reactor - Discharge Burn-up	U-235 / U-238 Weight Fraction	U-235 Mass (× 1,000 g/MT)	U-238 Mass (× 1,000 g/MT)
PWR 20 GWd/MT	0.97%	9.4	960.0
PWR 40 GWd/MT	0.89%	8.4	930.0
PWR 60 GWd/MT	0.59%	5.4	910.0
BWR 15 GWd/MT	0.80%	7.8	970.0
BWR 30 GWd/MT	0.81%	7.8	950.0
BWR 50 GWd/MT	0.59%	5.5	920.0

Figure 2 shows the mass of fissile plutonium (Pu-239 and Pu-241) as a function of discharge burn-up and time after discharge. The fissile Pu-239 and Pu-241 concentrations in discharge LWR fuel increases with increasing burn-up. While the concentration of Pu-239 remains relatively constant up to 100 years after discharge, the concentration of Pu-241 decreases significantly (14.35 year half-life). Table II shows what is defined as a "fissile plutonium concentration[2]" metric, given as the product of the isotopic concentration (g/MT) and the thermal fission cross section (barns), normalized by 10^6. This metric, while simplistic, shows that the "fissile plutonium concentration" in discharge LWR fuel increases with increasing burn-up. However, there is a 10% - 15% reduction in the "fissile plutonium concentration" 30 years after discharge, as compared to 5 years after discharge, and 17% - 22% reduction 100 years after discharge.

Figure 3 shows the transuranic composition (neptunium, plutonium, americium, and curium) of discharge LWR fuel. The concentration of all transuranic isotopes increases with increasing burn-up. The plutonium concentration decreases with time after discharge, as a result of the decay of Pu-241 to Am-241, leading to an increase in the total americium concentration. Am-241 also decays to Np-237, resulting in an increase in the Np-237 concentration with increasing time after discharge. The concentration of Cm, primarily Cm-244, decreases with increasing time after discharge.

Figure 3 also shows the composition of key fission product isotopes (Cl-36 Sr-90, Cs-137, I-129, Tc-99) that are important heat generating isotopes or have been shown to be important in the safety analyses of geologic disposal systems. The concentration of these isotopes all increase relatively linearly with increasing burn-up. The concentration of shorter-lived isotopes, Sr-90 and Cs-137, decreases with increasing time after discharge.

Figure 4 shows the decay heat of LWR discharge fuel as a function of burn-up and time after discharge. The results show a significant increase in the decay heat of 5-year cooled LWR fuel as function of burn-up due to increases in the concentration of Sr-90, Cs-137, plutonium, and americium isotopes. Cooling the fuel up to 30 years after discharge results in a large decrease in decay heat generation. This decrease continues, but not as drastically, with the decay heat beginning to converge for LWR fuel of all burn-up around 100 years.

[2] Detailed reactor physics calculations are required to determine the actual "fissile worth" of the plutonium that would be recovered if the used nuclear fuel were subsequently reprocessed and would include other materials that would be carried over. This metric is used to define a broad "fissile worth" of LWR plutonium.

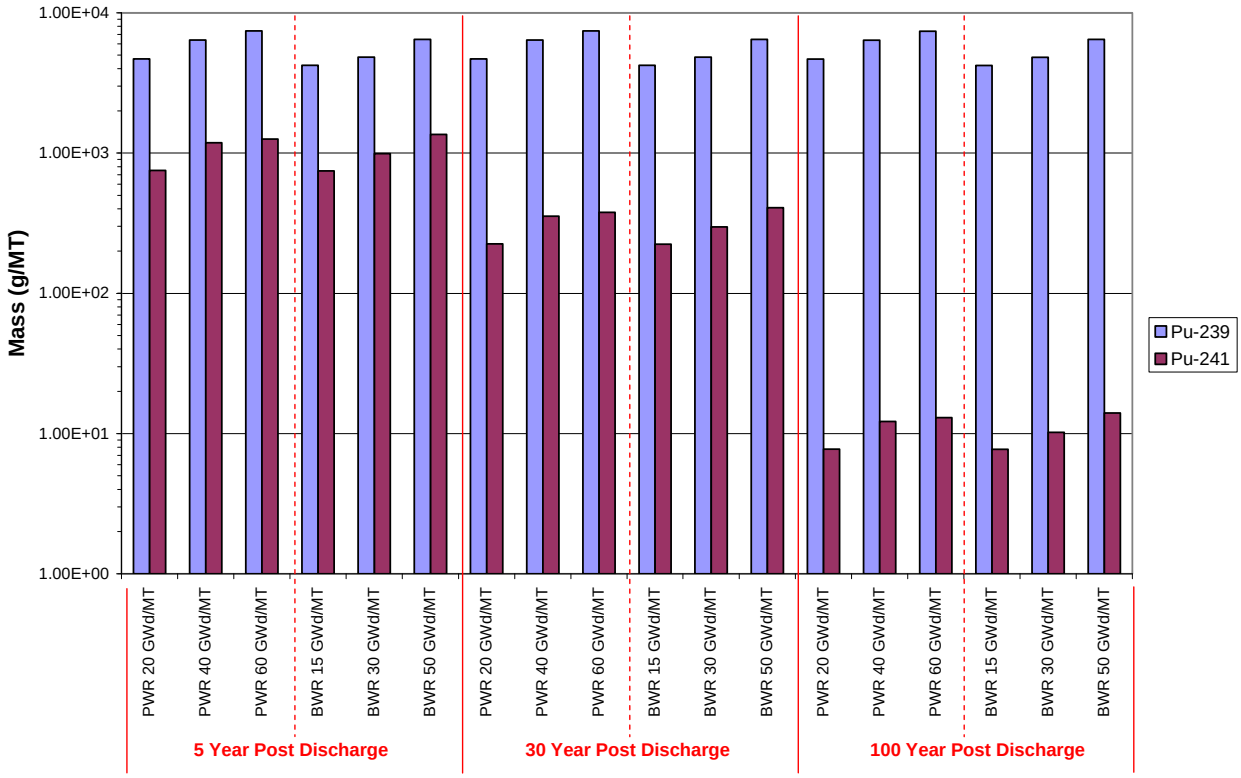

Fig. 2. Fissile plutonium isotopic inventory in discharge LWR fuel [from Ref. 3]

Table II. Fissile plutonium worth of discharge LWR fuel [from Ref. 3]

Reactor - Discharge Burn-up	Time After Discharge (yr)		
	5	30	100
PWR 20 GWd/MT	4.3	3.7	3.5
PWR 40 GWd/MT	6.0	5.2	4.8
PWR 60 GWd/MT	6.8	5.9	5.6
BWR 15 GWd/MT	3.9	3.4	3.2
BWR 30 GWd/MT	4.6	3.9	3.6
BWR 50 GWd/MT	6.2	5.3	4.9

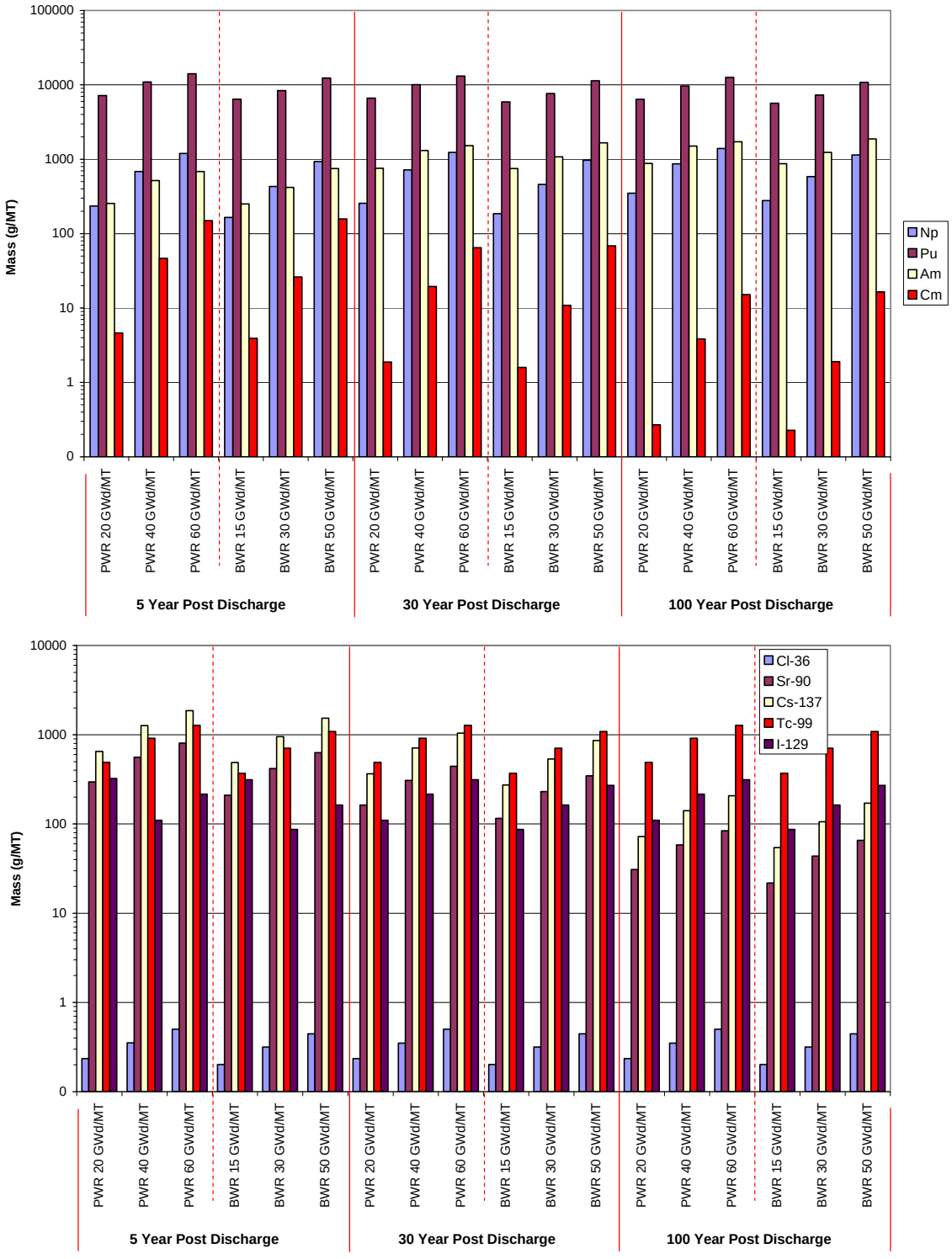

Fig. 3. Transuranic and fission product composition of discharge LWR fuel [from Ref. 3]

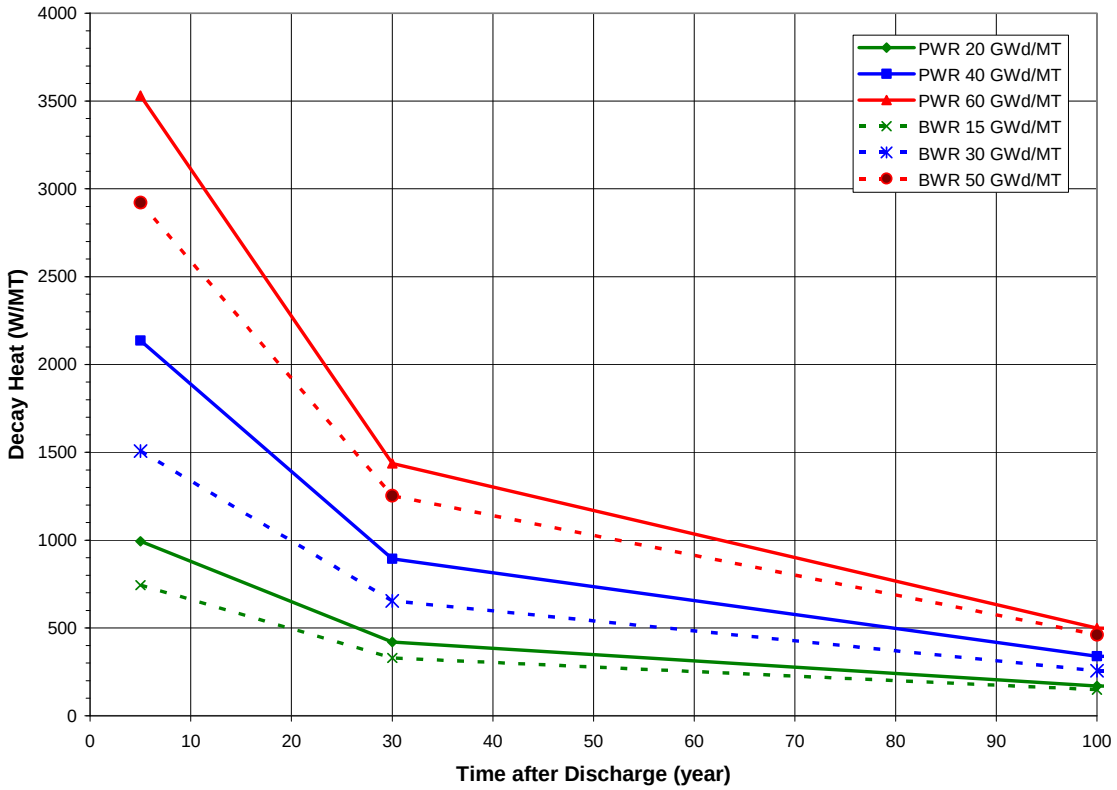

Fig. 4. Decay heat of discharge LWR fuel [from Ref. 3]

CONSIDERATIONS RELATED TO POTENTIAL UNF SELECTION CRITERIA

Current Reactor Fleet Operational Considerations

The contractual terms and conditions under which the DOE will make available nuclear waste disposal services to the owners and generators of spent nuclear fuel (SNF) are provided at 10 CFR 961. While the scope of 10 CFR 961 is on disposal services, a similar contractual agreement may be established for reprocessing services. The acceptance priority established in 10 CFR 961 is oldest fuel first. However, utilities have flexibility to request that younger fuel be accepted.

In response to delays in establishing a capability to dispose discharged nuclear fuel nuclear utilities have constructed and continue to construct dry independent spent fuel storage installations (ISFSI). The *de facto* limit on UNF that can be stored in an ISFSI is temperature. U.S. Nuclear Regulatory Commission (NRC) storage licenses require that cladding temperature in storage not exceed 400 ^{o}C, and higher temperatures may be allowed only for fuel with burn-up less than 45 GWd/MT [Ref. 4]. Thus, the fuel placed in an ISFSI is typically lower burn-up and cooler.

A nuclear utility may choose to select higher burn-up, shorter cooled fuel from the spent fuel pool for reprocessing over lower burn-up, longer cooled fuel from the ISFSI. Fuel assemblies residing in an ISFSI are no longer “competing” for valuable space in the spent fuel pool and a nuclear utility may have priority in increasing the capacity of the spent fuel pool and minimizing the number of fuel assemblies that would have to be moved into an ISFSI.

As such, a future reprocessing plant may be designed to accommodate higher fuel burn-up and shorter cooling times in order to be responsive to nuclear utility spent fuel management priorities and strategies. A reprocessing plant could be designed with lag storage or a regional/central off-site ISFSI could be constructed to "accept" shorter cooled fuel for subsequent decay storage and feed into a reprocessing plant.

Energy Production Considerations

The primary purpose of the nuclear fuel cycle is to produce energy, which must be done as cost-effective as possible. As such, there is incentive to minimize the cost of nuclear fuel. This would give incentive to increase the 'support ratio,' or the amount of discharged LWR fuel that would have to be recycled to generate energy in subsequent irradiation in a reactor. The 'support ratio' is a direct function of the fissile content within the fuel being recycled. A lower 'support ratio' would require more fuel having to be reprocessed to obtain the equivalent amount of fissile material that would be used to fabricate fuel.

Two sources of fissile material would be generated during reprocessing that could be recycled as fuel – recovered uranium and recovered plutonium. If recovered uranium were to be used it would have to be re-enriched. Table I clearly shows that uranium recovered from higher burn-up fuel would require more enrichment, exceeding that required for natural uranium at the burn-up levels that are or soon will be discharged.

While recovered uranium could be used, the primary fissile material considered in fuel cycles that involve recycling is plutonium (Pu-239 and Pu-241). As discussed above (see Figures 3 and 4), the fissile plutonium content increases with increasing burn-up and decreases with increasing storage time following discharge. Correspondingly, the 'support ratio' decreases with increasing burn-up and decreasing storage time. An estimate of the increase in the 'support ratio' that would be required is shown in Table III and was determined using the "fissile plutonium concentration" metric shown in Table II.

The unit cost for reprocessing considering a system of government owned reprocessing plants, each with a 40 year service life, that would reprocess spent nuclear fuel generated between 2010 and 2100 has been estimated [Ref. 5]. Sensitivity analyses conducted indicate that decreasing the discharge burn-up of LWR fuel from 52 to 47 GWd/MT would lead to an 11% increase in overall cost and results from the extra need for reprocessing capacity and storage to separate the equivalent fissile mass. The results shown in Table 2 indicate that even larger costs could be incurred over a wider range of burn-up and storage times between discharge and reprocessing.

Table III. Support ratio dependence (relative to 60 GWd/MT PWR and 50 GWd/MT BWR - 5 year cooled)

Reactor/Burn-up	Time After Discharge (yr)		
	5	30	100
PWR 20 GWd/MT	59.7%	82.4%	94.2%
PWR 40 GWd/MT	14.1%	32.7%	42.5%
PWR 60 GWd/MT	0.0%	15.0%	22.8%
BWR 15 GWd/MT	58.6%	83.3%	96.4%
BWR 30 GWd/MT	34.6%	58.6%	71.6%
BWR 50 GWd/MT	0.0%	18.3%	28.1%

Waste Management Considerations

A potential benefit of nuclear fuel cycles that include recycling is to gain efficiencies in managing highly radioactive materials. Two key aspects are typically considered: the ability to reduce the long-term risk of geologic disposal, and the ability to reduce the thermal output of the waste that would be disposed. Both depend on the isotopic concentrations of transuranic and fission products. The former is primarily dependent on the actinides Pu-239, Am-241, Np-237 and the fission products Tc-99 and I-129. The later is primarily dependent on the actinides Pu-238, Am-241, Cm-244, and the fission products Cs-137 and Sr-90.

The concentration of all fission products increases essentially linearly with burn-up (actually linearly with energy generation). Cm-244 (18.1 year half-life), Sr-90 (29 year half-life), and Cs-137 (30.2 year half-life) contribute primarily to the near-term decay heat while Am-241 (432 year half-life) and Pu-238 (87.7 year half-life) contribute primarily to the longer-term decay heat [Ref. 6]. Reducing the concentration of these isotopes reduces the thermal output of any material that would be disposed of in a geologic repository.

Lower burn-up, longer cooled discharge fuel has lower concentrations of these radionuclides and could be placed in a geologic repository sooner and at higher density. Waste forms that would be generated during reprocessing often have thermal limits and the waste loading density of such waste forms could be higher if lower burn-up, longer cooled fuel was reprocessed. However, overall thermal limits for a geologic disposal facility also play a role.

Reducing the concentration of these isotopes also has benefits with respect to loading storage and transportation casks that are thermally constrained. It is for these reasons that older fuel is typically placed in dry storage and the acceptance priority established in 10 CFR 961 is oldest fuel first.

Since the longer-lived fission products that could contribute to the long-term risk of geologic disposal are not readily amendable to transmutation, essentially every fuel cycle scenario envisions these isotopes ultimately being disposed of in a geologic repository. In addition, these radionuclides are very long-lived and do not decay appreciably during storage. As such, there is no clear difference in regard to reprocessing lower burn-up, older-cooler fuel as opposed to higher burn-up, younger-hotter fuel with respect to these isotopes. They will all have to be disposed.

Typically advanced fuel cycles involve the partitioning and subsequent transmutation of transuranic isotopes. Comparisons are made between the radiotoxicity of waste that would be generated from such fuel cycles with that of discharged LWR fuel. Radiotoxicity essentially represents the hazard of the material being disposed. This hazard, combined with the performance of the engineered and natural barriers offered by a geologic disposal system must be used to forecast the long-term risk. An evaluation of completed safety analyses in a variety of geologic environments indicates that the transuranic isotopes would only contribute to the overall risk for disposal in oxidizing environments and that they have minimal contribution in reducing environments [Ref. 7].

Thus, if focusing on radiotoxicity of the transuranic isotopes alone when prioritizing the fuel that would be reprocessed, Figure 3 indicates that higher burn-up fuel should be selected. This would result in a larger amount of transuranic isotopes being subject to further transmutation. The degree to which the inventory of these isotopes would be reduced depends on the fuel cycle scenario chosen (single- or multi-pass, thermal or fast spectrum). However, based on the discussion immediately above, the prioritization of discharge fuel to reprocess should not depend significantly on transuranic isotope inventories when considering the overall long-term risk of geologic disposal associated with these isotopes.

Transmutation Reactor Considerations

Repeated recycling using thermal reactors is possible, but results in steadily increasing decay heat and gamma source loads and the large increases in neutron emission rates would be particularly problematic [Ref. 8]. This is due to the build-up of higher actinides (Am-243, Cm-244) due to neutron absorption by Pu-241 within a thermal spectrum.

It has been pointed out that extended storage of discharged LWR fuel beyond 30 years would allow for the decay of Pu-241 into Am-241 which would subsequently be separated from the fission products, altering the actinide transmutation pathway to produce predominately lighter isotopes of plutonium instead of heavier actinides [Ref. 9]. Lower burn-up discharged legacy LWR fuel has lower concentrations of Pu-241 and, combined with decay storage, would lead to a reduced production of higher actinides in the first pass through a multi-step recycling scenario. This benefit would have to be weighed against the increased amount of separations that would be required due to the lower fissile content in the recovered plutonium.

A key advantage of using fast spectrum reactors resides in the high fission/absorption ratios. As identified by Taiwo and Hill [Ref. 10], for most fissile isotopes in a fast spectrum, nearly 90% of neutron absorptions result in fission, and fission fractions greater than 20% are observed for fertile isotopes. This results in the production of higher actinides being inhibited in a fast spectrum system. Thus, fast spectrum reactors would be capable of irradiating fuels fabricated from product derived from recycling discharged LWR fuel of any burn-up and cooling time.

Separations Plant Design, Construction, and Operations Considerations

The primary objective of a separations plant is to separate fissile material for subsequent use in a nuclear reactor to produce energy. As such, the fissile content of the input fuel stream, shown in Figure 2 and Table II, play a significant role. The higher the fissile content, the less fuel has to be processed to supply a reactor.

Evaluations of separations facilities conducted at the Savannah River Site as part of the Global Nuclear Energy Partnership investigated the impact of heat dissipation and radiation levels on the design, operation, and cost factors. The evaluation results indicated that since costs for heat disposal tend to be somewhat linear, and since the thermal management problem is both smaller and of shorter duration with aged fuel, lower heat loads may have the greatest impact on life cycle cost reduction. The evaluation also indicated that lower heat and radiation levels could lead to less shielding, smaller equipment or reduction of parallel capacity, less radiation damage to reagents, equipment and instrumentation, and less heat to dissipate.

It has been argued that there is a preferred “window” for reprocessing discharged LWR fuel between 30 and 70 years after discharge [Ref. 9]. Fuel that has been stored longer than 70 years may be more vulnerable to diversions and theft due to the decay of short- and intermediate-lived radioactive fission products that act as a “radiation barrier.” While recognizing that the existing separations plants are capable of processing 5-year cooled fuel, it is argued that reprocessing fuel that has been cooled less than 30 years following discharge leads to increased processing difficulty and environmental releases. The reasons cited for considering reprocessing fuel that has been stored longer than 30 years are:

- a 30 year cooling time allows for the decay of Pu-241 into Am-241, altering the actinide transmutation pathway to produce predominately lighter isotopes of plutonium instead of heavier actinides;
- the decay heat generation rate would be reduced; and
- the inventory of volatile species, such as krypton, xenon, and tritium, would be reduced and lower capacities and efficiencies of trapping systems would be needed to achieve the same regulatory level of emissions.

While there may be benefits that could be gained in terms of reprocessing facility design if older fuel were selected for reprocessing, it is likely that a future facility would be designed, constructed, and operated to be capable of processing higher burn-up fuel. This would provide maximum flexibility to a future fuel cycle and would be capable of processing a range of fuels over its design lifetime. As an example, in developing the draft Global Nuclear Energy Partnership Programmatic Environmental Impact Statement [Ref. 11], the U.S. Department of Energy assumed that a separation facility (both aqueous and electro-chemical) would be capable of processing fuel with burn-up up to 60 GWd/MT and cooled a minimum of 5 years after discharge.

Fuel Fabrication Considerations

Fuel fabrication plants currently used to manufacture uranium-plutonium mixed-oxide fuel, such as the MELOX plant in France and the Mixed Oxide Fuel Fabrication Facility, utilize glove boxes [Ref. 12]. This is because the radiation fields and heat generation rates are low. The burn-up of the discharge fuel and the amount of time it is stored prior to reprocessing would have no bearing for such a fabrication plant as it would be processing only plutonium.

The increased radiation fields and heat generation rates could impact the design of a fuel fabrication plant used to manufacture transuranic-bearing fuels for subsequent irradiation in either a thermal or fast neutron spectrum. Decreasing the concentration of these isotopes would reduce the heat generation rates and radiation fields, pointing to a potential benefit with respect to fabricating transuranic-bearing fuels by selecting discharge LWR fuel that has been stored for a longer period of time for recycling.

As with the reprocessing plant, while there may be benefits with regard to fabricating transuranic-bearing fuels derived from lower burn-up, longer cooled LWR fuel, it is likely that a future facility would be designed, constructed, and operated to be capable of processing product derived from higher burn-up fuel, shorter cooled fuel. Again, this would provide maximum flexibility to a future fuel cycle and would be capable of processing a range of fuels over its design lifetime. In addition, simply fabricating transuranic-bearing fuels will likely require remote and automated fabrication systems and active heat removal capabilities regardless of the burn-up or age of the fuel the transuranic product was derived from.

Proliferation

Increasing the discharge burn-up and minimizing the time the fuel is store prior to reprocessing may be slightly advantageous with regard to proliferation resistance. Increased burn-up and decay storage changes the plutonium vector. While total plutonium accumulates approximately as the square root of burn-up, the ratio of Pu-238/Pu-239 increases as approximately as burn-up to the 2.5 power and the ratio of Pu-240/Pu-239 increases approximately proportional to the burn-up [Ref. 13]. Pu-239 is the primary plutonium isotope desired for weapons use and it is disadvantageous to have the other plutonium isotopes (spontaneous fission and heat generation). Table IV provides the ratio of Pu-239 to total plutonium as a function of burn-up and time after discharge of LWR fuel [from Ref.. 3]. It can be seen that the Pu-239/total plutonium ratio decreases with increasing burn-up, but increases with time after discharge. Reprocessing higher burn-up, shorter cooled fuel would lead to a lower Pu-239/total plutonium ratio in the separated product.

Table IV. Pu-239 to total plutonium ratio in discharged LWR fuel

Reactor/Burn-up	Time After Discharge (yr)		
	5	30	100
PWR 20 GWd/MT	65.5%	70.7%	73.4%
PWR 40 GWd/MT	58.4%	63.4%	66.2%
PWR 60 GWd/MT	52.6%	56.2%	58.6%
BWR 15 GWd/MT	65.6%	71.5%	74.4%
BWR 30 GWd/MT	57.9%	63.3%	66.2%
BWR 50 GWd/MT	52.4%	56.8%	59.6%

CONCLUSION

A preliminary evaluation of the criteria that would potentially be considered in selecting discharged LWR for subsequent recycling has been completed. An initial consideration of these criteria indicates that sufficient higher burn-up discharged used LWR fuel having a wide range of cooling time would be available to support a future fuel cycle that would include recycling. It is expected that a future separations plant would be designed and constructed such that it would be capable of processing higher burn-up and shorter cooled fuel, but future decisions could be made regarding the age of the discharge fuel that would be selected. Lower burn-up, long-cooled legacy used fuel may be better suited for direct disposal in a geologic repository. These initial conclusions should be verified using more detailed systematic evaluations considering the criteria discussed above (along with any other criteria subsequently identified).

ACKNOWLEDGEMENT

Argonne National Laboratory is managed by UChicago Argonne, LLC, for the U.S. Department of Energy under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. The U.S. Government retains for itself and others acting on its behalf a nonexclusive, royalty free license, with the rights to reproduce, to prepare derivative works, and to display publicly.

REFERENCES

1. U.S. Department of Energy, Office of Nuclear Energy, *Nuclear Energy Research and Development Roadmap*, Report to Congress, April 2010.
2. U.S. Department of Energy, Office of Nuclear Energy, *Fuel Cycle Technologies, Program Management Plan*, July 2010.
3. J.T. CARTER and A.J. LUPTAK, Fuel Cycle Potential Waste Inventory for Disposition, U.S. Department of Energy, Office of Nuclear Energy Fuel Cycle Research and Development Program, FCR&D-USED-2010-000031 Rev. 2, September 2010.
4. M.A. McKINNON and M.E. CUNNINGHAM, Dry Storage Demonstration for High-Burnup Spent Nuclear Fuel – Feasibility Study, Pacific Northwest National Laboratory, PNNL-14390, August 2003.
5. E.A. SCHNEIDER, M.R. DEINERT, and K.B. CADY, Cost Analysis of the US Spent Nuclear Fuel Reprocessing Facility, Energy Economics, Volume 31, Issue 5, September 2009, pp. 627-634.

6. R.A. WIGLAND, T.H. BAUER, T.H. FANNING, and E.E. MORRIS, Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository, Nuclear Technology Vol. 156, April 2006. pp. 95-106
7. P.N. SWIFT and W.M. Nutt, Applying Insights from Repository Safety Assessments to Evaluating Impacts of Partitioning and Transmutation, 11th Information Exchange Meeting on Partitioning and Transmutation, OECD Nuclear Energy Agency, October 2010 (to be published).
8. T.K. KIM, J.A. STILLMAN, T.A. TAIWO, Argonne National Laboratory, Unpublished Information, 2002.
9. E.D. COLLINS, G.D. DEL CUL, J.E. RUSHTON, and K.A. WILLIAMS, A Practical Solution to Used Nuclear Fuel Treatment to Enable Sustained Nuclear Energy and Recovery of Vital Materials, ORNL/TM-2010/81, April 2010.
10. T.A. TAIWO and R.N. HILL, Argonne National Laboratory, Unpublished Information, 2007.
11. U.S. Department of Energy, Draft Global Nuclear Energy Partnership Programmatic Environmental Impact Statement, DOE/EIS-0396, October 2008.
12. Shaw AREVA MOX Services, LLC, Mixed Oxide Fuel Fabrication Facility License Application (Redacted), March 2010.
13. Z. XU, M.S. KAZIMI, and M.J. DRISCOLL, Impact of High Burnup on PWR Spent Fuel Characteristics, Nuclear Science and Engineering, Vol. 151, 2005. pp. 261-273.