The Impact of Burnup on the Performance of Alternative Fuel Cycles

by
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The Programmatic Environmental Impact Statement (PEIS) for the Department of Energy (DOE) Global Nuclear Energy Partnership (GNEP) program includes a number of fuel cycle alternatives. These alternatives range from the current fuel cycle to fuel cycles which have only been studied on paper. This has resulted in variation in the level of optimism involved with the data used for the different fuel cycles. One factor in particular is the burnup assumed for each type of fuel at the time of discharge from the reactor. Burnup refers to the amount of energy generated per initial mass of fuel, the metric tons of initial heavy metal (MTIHM). For fuel assemblies of equal initial mass and for a given total energy production, higher burnup fuels can reduce the total mass of spent fuel generated by providing more energy per fuel assembly, although each assembly would also contain a greater inventory of fission products and, for all enriched uranium-based fuels[1], a greater inventory of heavier actinide elements. This paper assesses and compares different discharge burnups and discusses the impact on a number of metrics, including spent nuclear fuel (SNF) quantities generated, transportation required, raw materials utilization, and waste parameters (long-term heat and long-term radiotoxicity).

Table 1 shows all of the alternatives that were analyzed in detail in the GNEP PEIS. This information is taken from Chapter 4, Table 4.8-4 of the PEIS. Other alternatives were also discussed briefly in the text of the PEIS, such as the "deep burn" alternative for the HTGR. Rather than a discussion of each reactor type, the reactors can be grouped by their neutron spectrum characteristics to determine the general impact of burnup, since the neutron spectrum affects the probability of neutron capture (absorption) or fission, which in turn will affect the composition of the discharged fuel.:

- Thermal spectrum – No Action, Thorium, HWR, LWR portion of all recycle alternatives and HWR portion of DUPIC alternative
- Epithermal spectrum –HTGR
- Fast spectrum – ARR portion of Fast and Thermal/Fast recycle alternatives

With such a grouping, the analysis in this paper should be sufficient to understand the impact of burnup on all of the alternatives.

Table 1 - PEIS alternatives indicating assumed reactor mixes and fuel burnup levels[1]

Case Description	No Action (Once-Through Fuel Cycle)	HWR or HTGR Alternative (Once-Through Fuel Cycle)		Thorium Alternative (Once-Through Fuel Cycle)	Thermal Recycle Alternative		Fast Recycle Alternative (CR=0.5)	Thermal /Fast Recycle Alternative (CR=0.5)
		All HWR	All HTGR		Option 1--LWR/LWR (MOX–U-Pu)	Option 2—LWR/HWR (DUPIC)		
Reactor Power Production*(100 GWe)								
LWR–UOX or HWR–UOX or HTGR–UOX	100 GWe LWR	100 GWe HWR	100 GWe HTGR	0	0	73 GWe LWR	60 GWe LWR	63 GWe LWR
LWR–MOX-U-Pu, or LWR-HWR	0	0	0	0	100 GWe LWR	27 GWe HWR	0	7 GWe LWR

[1] This includes the specific fuel in the Thorium Alternative, which uses enriched uranium as a driver in both the seed and blanket. Thorium fuels can also use plutonium as a driver.

Fast Advanced Recycling Reactor (ARR)	0	0	0	0	0	0	40 GWe ARR	30 GWe ARR
LWR–ThOX/UOX	0	0	0	100 GWe LWR	0	0	0	0
Fuel Burnup at Discharge (GWd/MTHM)	51	21	100	149 (UOX) 75 (ThOX)	45	35 (UOX) 15 (HWR)	51 (LWR) 107 (ARR)	51 (LWR) 50 (LWR – MOX/Pu) 105 (ARR)

Thermal Spectrum Burnup Trends

The greatest amount of data on thermal spectrum burnup and its impacts is available for uranium oxide fuels (UOX) used in Light Water Reactors (LWRs). Therefore, this paper begins with the no-action alternative of UOX-fueled LWRs, which coincides with the current U.S. commercial nuclear fleet. The impact of burnup on HWR, Thorium and MOX fuels would follow the same general trends.

Historical U.S. commercial reactor operations show a steady trend toward higher burnup (see Figure 1). The average improvement over the last 20 years is about 1 GWd/MTIHM per year. If this trend continues, burnup levels by 2020 will approach 60 GWd/MTIHM.

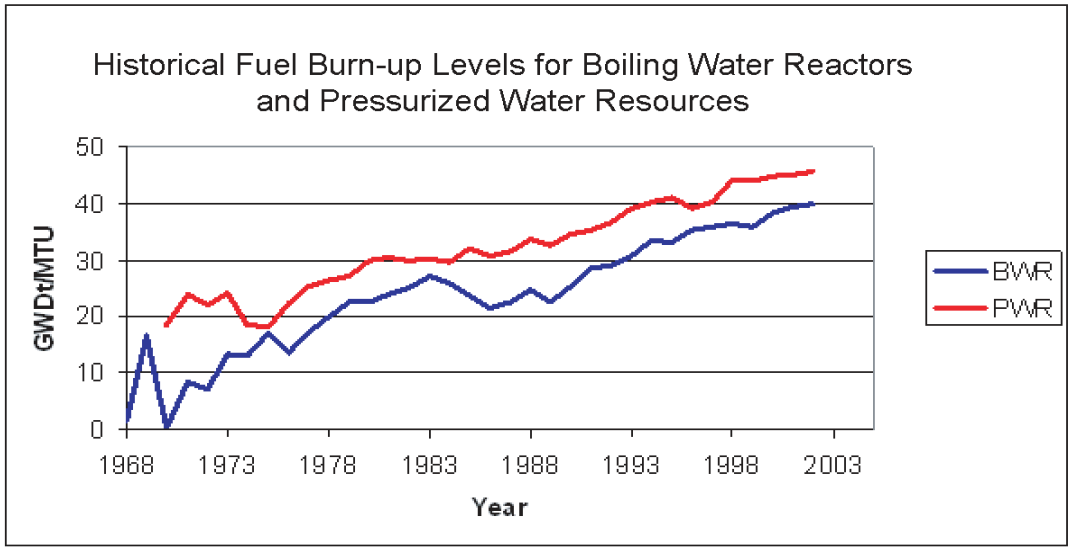

Figure 1 - Historical Fuel Burnup Levels for U.S. Commercial Boiling Water Reactors and Pressurized Water Reactors[2]

To assess the impact of burnup with thermal spectrum reactors, three LWR UOX burnup levels are considered (1) 33 GWdt/MTIHM, the average cumulative burnup in currently stored SNF[3], (2) 51 GWdt/MTIHM approximates current fuels in U.S. commercial reactors, and (3) 100 GWdt/MTIHM provides a higher value that has been suggested by an MIT study[4] and that is used as a bounding value for the Advanced Fuel Cycle Facility (AFCF) (see PEIS chapter 9). There are a number of practical limitations that suggest burnup increases may peak before this upper value is reached:

- Higher burnup means longer periods between refueling outages. Reactor owners complete significant maintenance during the refueling outages – the longer the time between outages, the more maintenance that builds up. Currently these outages are around every 18 months[5]. (Higher burnup could be achieved while maintaining current refueling schedules if the fuel was left in the reactor for more cycles.)
- High burnup fuels are beginning to exhibit a greater frequency of cladding failures[6], suggesting the upper limit for current cladding material and manufacturing processes is being reached for the reactor fuel power density being used today.
- Current enrichment facilities are only licensed up to 5% enrichment for commercial applications. While the average enrichment in today's fuels is below the 5% limit, enrichment between assemblies and within assemblies varies to support load balancing. Portions of fuel elements are now at the 5% limit. (New enrichment facilities could be designed and licensed for higher enrichment, or it may be possible to relicense older facilities for production at higher enrichment.)
- Higher burnup requires higher enrichment. The enrichment levels for 51 GWd/MTIHM and 100 GWd/MTIHM UOX fuel average 4.3% and 8.5% respectively (See Appendix A). This is an increase in enrichment from natural uranium (~0.7% enriched) of 3.6% and 7.8% or 0.071% and 0.078% per unit of burnup (GWd/MTIHM). So while the higher burnup produces double the energy per unit of fuel, the increase in enrichment is more than double.
- General economics may not support much higher burnup. Hesketh and Robbins[7] determined "A clear minimum in fuel cycle costs are seen at or below 55 GWd/MT" that is "robust against perturbations in the underlying assumptions" such as the price of uranium. Gregg and Worrall[8] similarly concluded that "there is no fuel cycle cost benefit in discharge burnups greater than 70 to 75 GWd/MT."

Higher burnup results in less SNF per unit of energy produced. The amount of SNF produced varies inversely to the SNF burnup - using the same reactor with the same thermal efficiency, increasing burnup by 50% decreases SNF by 33% (1.0/1.50) and doubling the burnup cuts SNF in half (1.0/2.0). The relationship is roughly linear over this range. This equates to fewer shipments of fresh fuel, but spent fuel shipments may not decrease linearly (or at all) due to the higher radiation and decay heat levels in the spent fuel. If the spent fuel shipments are volume limited, then half as much SNF may mean half as many shipments. But if they are limited by decay heat or shielding requirements (or by weight, which is often driven by shielding) then the number of SNF shipments may not be reduced significantly. This is because with higher burnup the same number of fissions have taken place, but within fewer fuel assemblies – and those fewer assemblies still contain the same total masses of highly radioactive fission products. Since the fission products are more concentrated, each assembly is hotter (both radioactively and thermally) approximately in proportion to the increase in burnup. Appendix E of the PEIS indicates SNF shipments are limited by both volume and thermal considerations. The thermal impact can be somewhat reduced by storing the fuel longer before shipping, giving more time for the shorter-term fission products to decay. Appendix A of this paper lists the percent quantities of isotopes remaining in LWR UOX SNF at different burnups that have been cooled for 5 years after discharge. Total shipments are highly dependent on natural, enriched, and depleted uranium shipments on the fuel cycle front end, which is driven primarily by the amount of uranium needed per unit of energy produced.

Higher burnup also results in higher levels of heavier elements in the SNF. This is because there is more time for multiple neutron captures by the uranium atoms. Some of the created isotopes subsequently fission, such as some of the highly fissionable Pu-239 that is created through neutron capture by fertile U-238. This contributes to improved uranium utilization (since both U-

235 and U-238 contribute to power production by fissioning). However, other created heavier isotopes are typically long-lived and therefore contribute to both long-term decay heat and long-term radiotoxicity. These heavier isotopes and their initial decay products include the transuranics, additional uranium isotopes, and other actinides.

Table 2 highlights several factors impacted by discharge burnup (derived from reference 9). The table shows uranium and SNF quantities based on operating equivalent LWRs with each fuel type. It also shows changes in the long-term heat (LTH) and long-term radiotoxicity (LTR). Long-term heat is based on the summation of decay heat output from 100 to 1500 years after discharge, which addresses the drift loading limitation caused by the between-drift temperature peak for the current repository design. Using a discharge burnup of 33 GWd/MTIHM as a reference, Table 2 shows both the change per unit of energy produced, which affects disposal requirements, and the change per fuel assembly, which affects handling, storage, and shipping. While the LTH and LTR decreases with increasing burnup, the decrease is not substantial, indicating that there would only be a modest beneficial impact on disposal of the spent fuel. The decay heat load and radiotoxicity per fuel assembly climbs considerably due to the higher concentrations of both fission products and heavier isotopes, greatly impacting handling, storage, and shipping.

Table 2 – Performance versus burnup for UOX for equivalent energy output (relative to 33 GWd/MTIHM fuel)[9]

	UOX-33	UOX-51	UOX-100
Natural Uranium needed:			
For equivalent energy produced	100%	88%	91%
Average U-235 enrichment*	3.2%	4.3%	8.5%
Spent Fuel produced:			
For equivalent energy produced	100%	65%	33%
Per fuel assembly	100%	100%	100%
Fission Products produced:			
For equivalent energy produced	100%	100%	100%
Per fuel assembly	100%	155%	303%
Long-term heat:			
For equivalent energy produced	100%	95%	81%
Per fuel assembly	100%	147%	246%
Long-term radiotoxicity:			
For equivalent energy produced	100%	89%	79%
Per fuel assembly	100%	138%	241%

* Absolute values (instead of relative)

The radiotoxicity value used in Table 2 was based on a single point in time (1,000 years). Since the environmental impact of radiotoxicity is dependent on how long it takes for the material to migrate out of a repository and into the environment, the radiotoxicity as a function of time is needed. Figure 2 provides the radiotoxicity per gram of fuel out to 10 million years, showing that the relative magnitude of radiotoxicity for the different burnups remains similar across the full time span, justifying the use of a ratio at any particular time as a measure of the impact of burnup. Figure 3 indicates which portions of the SNF are contributing to radiotoxicity at different time periods (normalized to the radiotoxicity of the natural uranium that was required to make the fuel).

The same parameters affecting direct disposal of the spent fuel are also important if the fuel is recycled. The mass of radioactive material in the HLW resulting from recycling is driven primarily by the fission product content of the SNF. If burnup doubles, the amount of fission

products per fuel assembly approximately doubles, but resulting in almost no impact on the HLW on the basis of energy production. A second contributor to HLW is the transuranics (TRU). If all transuranics are recycled efficiently, the TRU mass lost to the HLW stream is minimal, but still important to long term radiotoxicity. However, if some or all of the minor actinides (Np, Am and Cm) are sent to waste then they also contribute significantly to the HLW stream. When considering both fission products and TRU, the mass of radioactive material in HLW increases roughly, but not quite, in proportion to the burnup per MT (and per fuel assembly) of SNF processed. The net result is little change in the HLW on an energy-generated basis. The other significant waste contributor in recycling is fuel cladding. The amount of cladding is the same per MT (and per fuel assembly) of SNF, independent of burnup. With reprocessing, this material is assumed to become greater-than-class-C (GTCC) waste.

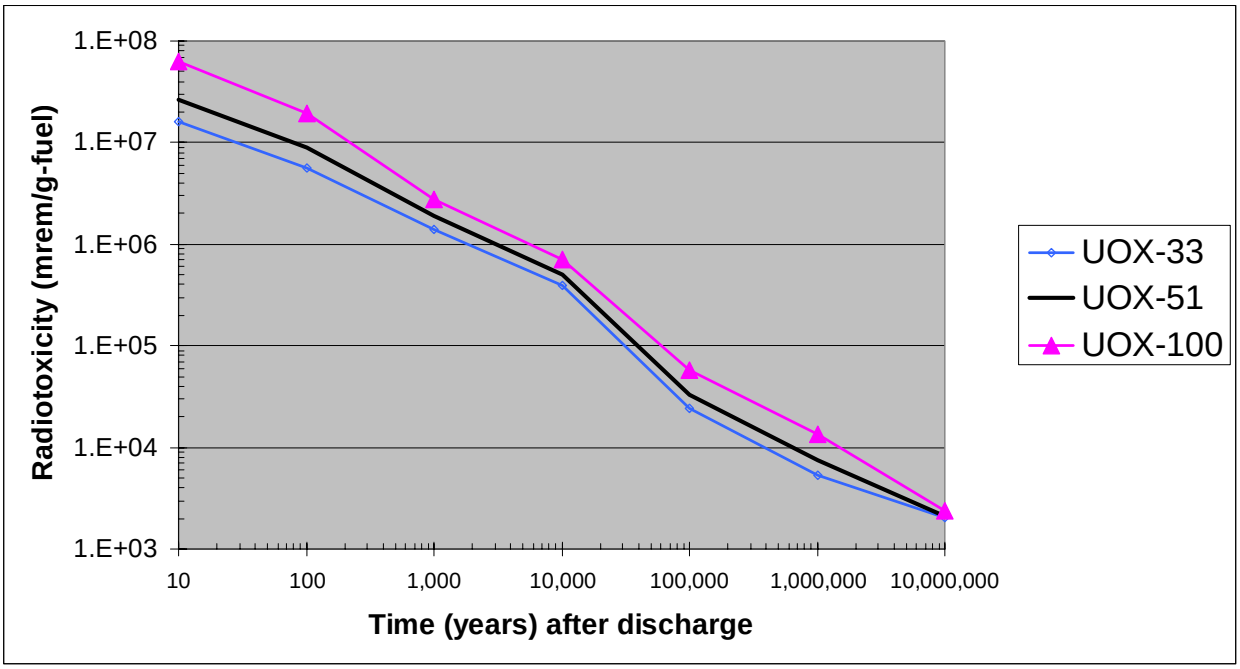

Figure 2 - Radiotoxicity of UOX, showing the impact of burnup from 33 to 100 GWd/MTHM[9]

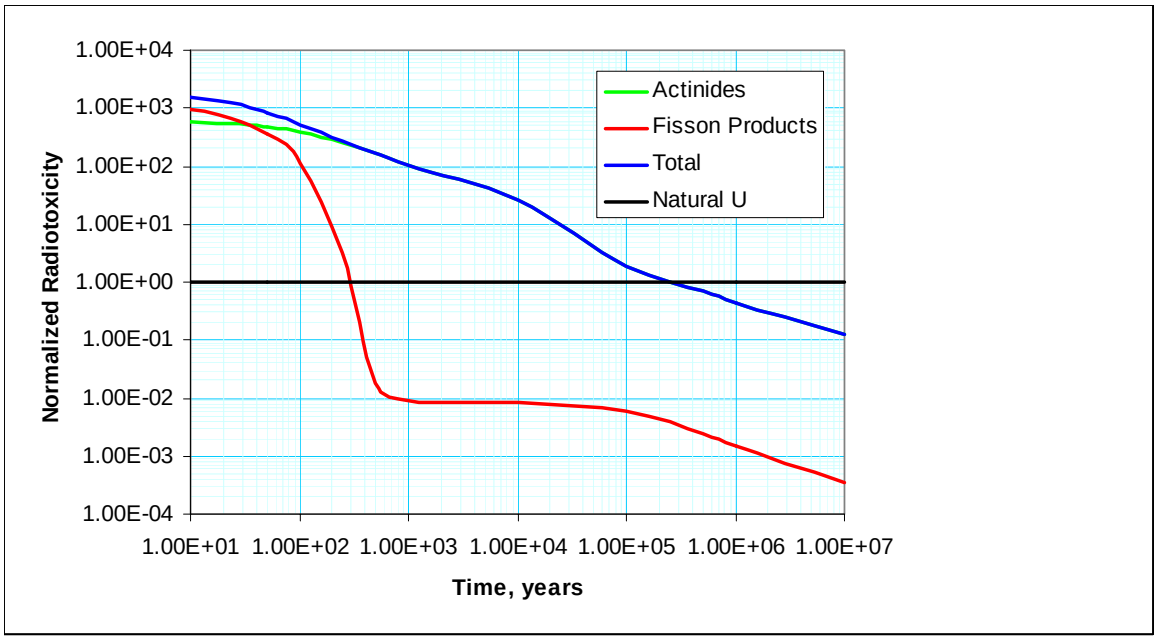

Figure 3 - Radioxicity of 51 GWd/MTHM spent UOX fuel showing primary contributors as a function of time after discharge[9]

In summary for UOX in the once-through case, for equivalent energy production higher burnup results in lower amounts of SNF (in terms of MTIHM) in proportion to the increase in burnup, but roughly the same amount of natural uranium is required and each SNF fuel assembly is both hotter and more radiotoxic, not quite in proportion to the increase in burnup. As a result, there is limited benefit for direct disposal of the spent fuel with increasing burnup. Transportation shipments may not be reduced due to thermal limits on SNF shipments and the potential for greater shipping requirements on the fuel cycle front end (since very high burnups require more natural uranium per unit of energy produced, more ore and UF6 shipments would be needed). If the UOX fuel is recycled, the mass of radioactive materials in HLW is roughly the same per unit of energy produced (but much higher per MT of SNF). The amount of GTCC waste attributable to the cladding and assembly hardware scales closely with the MT of SNF recycled.

Epithermal Spectrum Burnup Trends

The presentation on thermal spectrum burnup trends discussed the important characteristics and explained the relative insentitivity of the performance measures to changes in discharge burnup. This section presents the results of varying burnup in an epithermal spectrum using available data (see Table 3). The basic trends are the same with the following exceptions:

- Natural uranium usage for equivalent energy production appears to decline with higher burnup. This may be a different trend from the thermal spectrum or may just reflect a smaller range analyzed, from 51 to 100 GWd/MTIHM. Between 33 and 51 GWd/MTIHM, the results presented in the previous section for the thermal spectrum also showed less uranium usage as burnup increased, but the trend reversed at higher burnups.
- The difference in initial enrichment appears small, increasing from 10% to 14% for double the burnup, but the final enrichment at discharge is ~5-6%, so the decrease in U-235 content is roughly equal as a function of burnup.

- Both long-term heat and long-term radiotoxicity for equivalent energy production did not decline as much as in the thermal spectrum, but the trend direction was still the same.
- There are some differences that may be due to the way the increase in burnup was achieved – both enrichment and total heavy metal mass were varied to obtain the different burnups while for the thermal spectrum case only enrichment changed.

In summary, the burnup trends in the epithermal spectrum are similar to those in the thermal spectrum.

Table 3 – Performance versus burnup for HTGR fuel (relative to 50 GWd/MT fuel)[10]

	HTGR-50	HTGR-100
Natural Uranium needed:		
For equivalent energy produced	100%	72%
Average U-235 enrichment*	10.0%	14.0%
Spent Fuel produced:		
For equivalent energy produced	100%	51%
Per fuel assembly	100%	117%
Fission Products produced:		
For equivalent energy produced	100%	96%
Per fuel assembly	100%	220%
Long-term heat:		
For equivalent energy produced	100%	98%
Per fuel assembly	100%	224%
Long-term radiotoxicity:		
For equivalent energy produced	100%	96%
Per fuel assembly	100%	221%

* Absolute values (instead of relative)

Fast Spectrum Burnup Trends

Tables 4 and 5 provides the burnup trends for the fast spectrum. While the increase in burnup for the LWR was achieved by only increasing the initial fuel enrichment, the increase in burnup for the fast spectrum data was achieved either by increasing mass of the core, reducing power density, and keeping about the same enrichment, or by varying the enrichment, conversion ratio, and power density. Either approach makes it difficult to obtain results for all of the parameters of interest. The data presented in Table 4 are for a constant transuranic conversion ratio (of 0.5) and TRU enrichment, with the fluence limit varying with burnup. In Table 5, the conversion ratio is varied (from 0.0 to 1.0) along with the TRU enrichment, but the fluence limit is held constant. Since so many factors are changing, it is not clear in some areas whether the observed trends are due to the change in burnup or due to another factor. The apparent trends are as follows:

- The amount of uranium needed per equivalent energy production was not analyzed because for a burner fast reactor it is dependent on the LWR SNF that provides the makeup transuranics and whether makeup uranium in the fast reactor fuel is recycled, natural, or depleted.
- Spent fuel production per equivalent energy production trended similar to the thermal spectrum as burnup increased, but the changing heavy metal mass in the core makes the comparison difficult.
- Long term heat per equivalent energy production shows the same slightly downward trend as the other spectrums when varying the fluence limit, but was essentially

unchanged when varying the conversion ratio. In both cases the calculation is based on the material that would be disposed after reprocessing, assuming 0.1% loss of actinides.

- Long term radiotoxicity was not assessed but should trend similar to long term heat.

Table 4 – Performance versus burnup for ARR fuel with constant CR (relative to 132 GWd/MT fuel)[11]

	ARR-132	ARR-231
Burnup	100%	175%
Natural Uranium needed:		
For equivalent energy produced	Not analyzed	
Spent Fuel produced:		
For equivalent energy produced	100%	57%
Per fuel assembly	100%	120%
Fission Products produced:		
For equivalent energy produced	100%	96%
Per fuel assembly	100%	203%
Long-term heat:		
For equivalent energy produced (after processing)	100%	89%
Per fuel assembly (after processing)	100%	188%
Long-term radiotoxicity:	Not analyzed	

Table 5 – Performance versus burnup for ARR fuel with constant fluence (relative to 132 GWd/MT fuel)[12]

	ARR-73 CR=1.0	ARR-100 CR=0.75	ARR-132 CR=0.5	ARR-186 CR=0.25	ARR-294 CR=0.0
Burnup	55%	75%	100%	141%	233%
Natural Uranium needed:					
For equivalent energy produced	Not analyzed				
Spent Fuel produced:					
For equivalent energy produced	181%	132%	100%	71%	45%
Per fuel assembly	163%	139%	100%	67%	42%
Fission Products produced:					
For equivalent energy produced	100%	97%	100%	102%	100%
Per fuel assembly	90%	103%	100%	97%	93%
Long-term heat:					
For equivalent energy produced (after processing)	99%	103%	100%	103%	102%
Per fuel assembly (after processing)	89%	108%	100%	97%	94%
Long-term radiotoxicity:	Not analyzed				

The general conclusion on the effect of discharge burnup on spent fast reactor fuel is that the HLW resulting from processing will be relatively unaffected by changes in burnup, with the result that disposal needs will be unaltered, although handling, storage, and shipping may be affected in the same manner as for the other cases.

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[1] Wigeland, Roald, *Performance Summary of Advanced Nuclear Fuel Cycles, Rev 0, GNEP Report # TBD, March 2008.*

[2] Dixon, Brent and Piet, Steven "Impact of Nuclear Energy Futures on Advanced Fuel Cycle Options," Americas Nuclear Energy Symposium, Miami Beach, FL, October 2004.

[3] Energy Information Administration, *Table 3. Annual Spent Fuel Discharges and Burn-up, 1968-2002*, http://www.eia.doe.gov/cneaf/nuclear/spent_fuel/ussnfdata.html, October 2004.

[4] MIT, *The Future of Nuclear Power, An Interdisciplinary MIT Study*, http://web.mit.edu/nuclearpower/, 2003.

[5] Bodansky, David, *Nuclear Energy: Principles, Practices, and Prospects*, 2nd edition, Springer, 2004.

[6] Moore, Taylor, *The Challenge of Nuclear Fuel Reliability*, http://mydocs.epri.com/docs/CorporateDocuments/EPRI_Journal/2005-Fall/1012885_NuclearFuel.pdf, 2005.

[7] Robbins, C., Hesketh, K. W., Gresley, J. A. B., *Technical and commercial aspects of the use of reprocessed uranium TopFuel '97*, Proceedings of the Conference 3/25-34 Vol. 1, 1997.

[8] Gregg, R, A. Worrall, *Effect of highly enriched/highly burnt UO2 fuels on fuel cycle costs, radiotoxicity, and nuclear design parameters*, NUCL TECHNOL 151 (2): 126-132, August 2005.

[9] Piet, S. J., G. E. Matthern, J. J. Jacobson, C. T. Laws, L. C. Cadwallader, A. M. Yacout, R. N. Hill, J. D. Smith, A. S. Goldmann, and George Bailey, 2006, *Fuel Cycle Scenario Definition, Evaluation, and Trade-offs*, August 2006, INL/EXT-06-11683.

[10] Spreadsheet provided by Temitope Tiawo via email, April 8, 2008.

[11] Spreadsheet provided by Ed Hoffman via email, April 10, 2008.

[12] Spreadsheet provided by Ed Hoffman via email, April 10, 2008.

Appendix A. UOX Fresh and Spent Fuel Compositions

This appendix documents the fuel compositions (input and 5-year after discharge) for the calculations in this study. All units in the following tables are mass fractions; the total of heavy metal (actinides, U, TRU) and fission products equals 1. Some totals deviate slightly due to round-off errors.

The depletion calculations were performed using the ORIGEN-2[a] computer code. ANL has performed ORIGEN2 calculations using the one-group cross sections that were provided with the code. No separate WIMS8[b] cell calculations were performed to obtain new cross sections at those burnups. Another set of calculations was performed by BNL for the ultra-high burnup UOX fuel with 100 GWd/tonne, validated by calculations at ANL. In this case, ANL performed the WIMS8 cell calculations to estimate the one-group cross sections for ORIGEN2 calculations, instead of using the cross sections provided with ORIGEN2 (which did not provide reasonable results). WIMS8 calculations used 172-group, JEF2.2-based cross section library which has been previously determined to provide accurate modeling of the important Pu-239, Pu-240, and Pu-241 resonances. ANL results for this ultra-high burnup UOX calculation were compared to BNL results listed here, and the two sets of results were found to be comparable.

Table A-1. Once-Through Recipes for Input Fresh Fuel

	Once-through		
MASS FRACTIONS	UOX-33	UOX-51	UOX-100
Burnup (GWth-day/tonne-HM)	33	51	100
U234	0.0003	0.0003	0.0000
U235	0.0320	0.0430	0.0850
U236			
U238	0.9678	0.9567	0.9150
U	1.0000	1.0000	1.0000

Table A-2. Once-Through Recipes for 5-years after discharge

	Once-through		
MASS FRACTIONS	UOX-33	UOX-51	UOX-100
Burnup (GWth-day/tonne-HM)	33	51	100
Ra226	1.04E-13	2.68E-13	1.10E-14
Ra228	9.10E-20	1.81E-19	0.00E+00
Ac227	2.67E-14	1.17E-13	2.26E-15
Ac228	9.50E-24	1.89E-23	0.00E+00
Th229	2.05E-13	2.78E-12	5.02E-14
Th230	3.19E-09	5.10E-09	5.96E-10
Th231	3.28E-14	3.11E-14	0.00E+00
Th232	7.19E-10	1.25E-09	1.89E-09
Th234	1.37E-11	1.34E-11	1.24E-11
Pa231	2.66E-10	9.65E-10	4.55E-11
Pa233	1.16E-11	2.11E-11	5.90E-11
U232	1.34E-10	9.90E-10	1.12E-08
U233	1.89E-09	3.26E-09	3.71E-09
U234	1.60E-04	1.84E-04	6.64E-05
U235	8.06E-03	7.65E-03	9.35E-03
U236	3.87E-03	5.71E-03	1.25E-02
U238	9.44E-01	9.21E-01	8.56E-01
Np237	3.41E-04	6.21E-04	1.74E-03
Pu238	1.16E-04	3.07E-04	1.19E-03
Pu239	5.13E-03	6.15E-03	7.73E-03

Pu240	2.26E-03	2.92E-03	3.97E-03
Pu241	9.62E-04	1.38E-03	1.96E-03
Pu242	4.73E-04	8.64E-04	1.52E-03
Pu244	1.25E-08	2.86E-08	7.01E-08
Am241	2.90E-04	4.38E-04	6.55E-04
Am242m	3.48E-07	8.34E-07	2.90E-06
Am242	4.16E-12	9.98E-12	3.74E-11
Am243	7.90E-05	1.98E-04	4.71E-04
Cm242	5.83E-09	1.32E-08	2.72E-08
Cm243	2.13E-07	6.83E-07	1.67E-06
Cm244	1.83E-05	7.08E-05	2.48E-04
Cm245	1.03E-06	5.72E-06	3.07E-05
Cm246	9.56E-08	7.29E-07	5.57E-06
Cm247	8.40E-10	9.97E-09	1.21E-07
Cm248	4.33E-11	7.70E-10	1.45E-08
C14	2.63E-11	4.05E-11	7.92E-11
Sr90	4.77E-04	7.00E-04	1.41E-03
Zr93	7.19E-04	1.09E-03	2.18E-03
Tc99	7.86E-04	1.14E-03	1.99E-03
I129	1.83E-04	2.75E-04	4.58E-04
Cs135	3.06E-04	6.60E-04	1.37E-03
Cs137	1.07E-03	1.62E-03	3.04E-03
Ra	1.20E-13	3.89E-13	1.11E-12
Ac	2.67E-14	1.17E-13	2.26E-15
Th	3.92E-09	6.39E-09	2.72E-09
Pa	2.77E-10	9.86E-10	1.05E-10
U	9.56E-01	9.34E-01	8.78E-01
Np	3.41E-04	6.21E-04	1.74E-03
Pu	8.93E-03	1.16E-02	1.64E-02
Am	3.70E-04	6.38E-04	1.13E-03
Cm	1.97E-05	7.80E-05	2.86E-04
Other Actinides	5.99E-07	1.91E-06	0.00E+00
Total actinides	0.9659	0.9474	0.8974
Sr	8.28E-04	1.23E-03	2.52E-03
Zr	3.49E-03	5.30E-03	1.11E-02
Tc	7.87E-04	1.14E-03	1.99E-03
I	2.39E-04	3.59E-04	5.94E-04
Cs	2.54E-03	3.95E-03	7.20E-03
Other FP	2.62E-02	4.07E-02	7.92E-02
Total FP	0.0341	0.0526	0.1026

[a] A. G. Croff, ORIGEN2 – A Revised and Updated Version of the Oak Ridge Iosotope Generation and Depletion Code, Oak Ridge National Laboratory, ORNL-5621 (1980).

[b] WIMS - A Modular Scheme for Neutronics Calculations, User's Guide for Version 8, Serco Assurance.