Evaluation of Waste Arising from Future Nuclear Fuel Cycle – 15197[a]

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ABSTRACT

A comprehensive study was recently completed at the request of the US Department of Energy Office of Nuclear Energy (DOE-NE) to evaluate and screen nuclear fuel cycles. The final report was issued in October 2014. Uranium- and thorium-based fuel cycles were evaluated using both fast and thermal spectrum reactors. Once-through, limited-recycle, and continuous-recycle cases were considered. This study used nine evaluation criteria to identify promising fuel cycles. Nuclear waste management was one of the nine evaluation criteria. The waste generation criterion from this study is discussed herein.

The fundamental characteristics of nuclear fuel cycles were used to create a comprehensive set of fuel cycle options. These options were categorized into 40 Evaluation Groups based on similarities in their physics-based performance. These Evaluation Groups, listed below, comprehensively represent all fuel cycle options:

- 8 once-through Evaluation Groups: 5 uranium-based fuel cycles and 3 thorium-based fuel cycles,
- 10 limited-recycle Evaluation Groups: 6 uranium-based fuel cycles and 4 thorium-based fuel cycles, and
- 22 continuous-recycle Evaluation Groups: 14 uranium-based fuel cycles and 8 thorium-based fuel cycles.

The study focused on the quantity and characteristics of radioactive wastes generated by the different fuel cycles, examining 5 metrics characterizing waste generation:

- mass of spent nuclear fuel (SNF) plus high level waste (HLW) disposed per energy generated,
- activity of SNF + HLW (at 100 years) per energy generated,
- activity of SNF + HLW (at 100,000 years) per energy generated,
- mass of depleted uranium (DU) + recovered uranium (RU) + recovered thorium (RTh) disposed per energy generated, and
- volume of low level radioactive waste (LLW) per energy generated.

INTRODUCTION

In late 2011, the US Department of Energy Office of Nuclear Energy (DOE-NE) chartered the Evaluation and Screening Study [1] of nuclear fuel cycle options. The study's charter specified that the evaluation and screening consider the entire fuel cycle, to include the complete nuclear energy system, from mining to disposal. This would include both once-through and recycle fuel cycles to identify a relatively small number of promising fuel cycle options with the potential for achieving substantial improvements compared to the current nuclear fuel cycle in the US.

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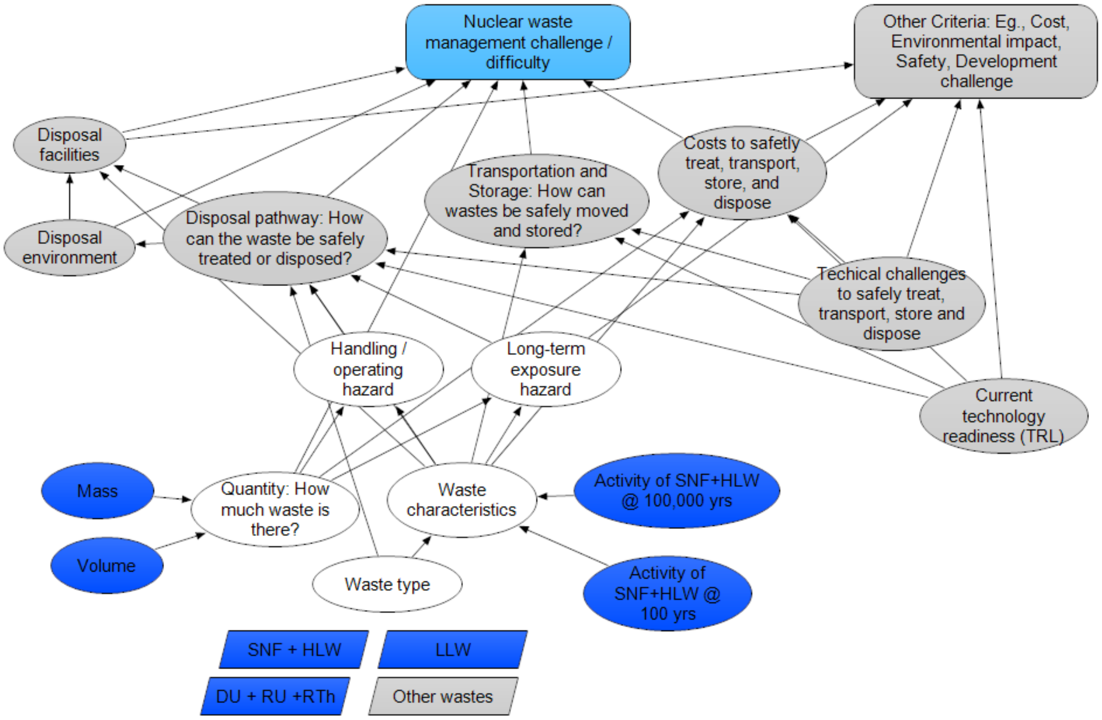
To achieve the objectives of the study, the charter specified that the improvement potential of the promising fuel cycle options would be measured in terms of broadly defined economic, environmental, safety, nonproliferation, security, and sustainability goals. The charter also specified nine high-level evaluation criteria, one of which was nuclear waste management. The results of that study were issued in 2014 [2].

Nuclear waste management is broadly defined as the safe and effective storage, transportation, and disposal of all radioactive material that is considered waste. For the purpose of this study, the assessment focused on generation of radioactive wastes requiring disposal, including any spent nuclear fuel (SNF), high-level waste (HLW), excess fuel material, and low-level radioactive waste (LLW). Since adequate disposal capability is required by any fuel cycle in the context of this study, the premise was that appropriate disposal would be available for any nuclear fuel cycle. By concentrating on waste generation, the study focused on the effects that fuel cycle options may have on the available disposal paths.

Metrics for Nuclear Waste Management

The management of radioactive waste from nuclear energy production is an important consideration for civilian use of nuclear technology and is often identified as a key issue for the future of nuclear energy. While all technologies create wastes that must be managed, the potentially concentrated radioactive nature of nuclear waste is unique and results in a high level of societal concern on how it is managed. Fig. 1 is an influence diagram showing some key factors that impact nuclear waste management, along with the relationships among those factors.



Note: Each oval represents a factor, element, or question on nuclear waste management. Rounded rectangles represent different high level evaluation criteria for the evaluation and screening. Dark blue indicates factors for which evaluation metrics were defined, and white indicates factors related to nuclear waste generation that are strongly driven by the characteristics of the fuel cycle. Gray indicates other nuclear waste management factors not included explicitly in the evaluation metrics for this criterion.

Fig. 1. Influence Diagram: Some Factors Affecting the Challenge of Nuclear Waste Management.

Numerous factors are relevant to the overall challenge of managing nuclear waste. The five evaluation metrics discussed below focus on waste quantity and waste characteristics. They are shown by the four blue ovals and three highlighted waste categories in Fig. 1, and they are described in additional detail below. In order to provide a consistent basis for comparing fuel cycles, all metrics were normalized to a per-unit-energy-generated basis.

Waste quantity: The mass of SNF+HLW is a characteristic of the fuel cycle at the functional level, while volume of SNF+HLW is dependent on the technologies chosen to implement the fuel cycle. Metrics for waste quantity are (1) mass of SNF+HLW per energy generated, (2) mass of depleted uranium (DU) plus recovered uranium (RU) plus recovered thorium (RTh) disposed per energy generated, and (3) volume of LLW produced per energy generated.

Waste characteristics: The high level of radioactivity of the SNF+HLW drives the requirements for shielding during handling / storage and isolation for disposal. One evaluation metric was selected for its ability to inform on the operational and handling challenges associated with SNF and HLW. While such a metric could be expressed in terms of heat generation, radiotoxicity or radiation field, all of these are caused by the total radioactivity, or “activity.” As the activity (or any of these other measures) changes with time, it is necessary to select a representative time for operations and handling for disposal. Many waste management approaches include a significant delay prior to disposal to allow the initial very high level of activity to decay. A time period of 100 years after discharge from a reactor was selected as being representative for the metric. Similarly, a total activity at a representative time for geologic disposal is relevant to a range of issues, including the radiotoxicity of the disposed wastes, and is dependent on the fundamental characteristics of the fuel cycle. A time of 100,000 years was chosen to represent the long-term isolation challenge. Therefore, metrics for waste characteristics are (1) activity of SNF+HLW at 100 years per energy generated, and (2) activity of SNF+HLW at 100,000 years per energy generated.

METHODOLOGY

This study evaluated and screened nuclear fuel cycles *only* at what is termed the “functional” level, using the fundamental physics characteristics of each step in a fuel cycle (i.e., the physics principles defining *what* happens at each fuel cycle step, not the technologies for *how* it is accomplished) both to enable creation of a comprehensive set and to provide flexibility for future R&D directions into specific technology choices. For example, a pressurized-water reactor (PWR) is a specific technology for implementing the function of thermal neutron irradiation. Similarly, reprocessing using Plutonium Uranium Extraction better known as PUREX to isolate and recover plutonium is a specific technology for implementing the function of recovering plutonium from irradiated fuel for reuse (which does not necessarily require isolating plutonium). The Evaluation and Screening Team (EST) conducted this study at such a functional level, analyzing thermal neutron irradiation, plutonium recovery, and many other possible fuel cycle functions. As a consequence, the study did not evaluate or screen either specific technology options or implementation / deployment options. Some important aspects of the functional level evaluation are described below.

- The nuclear fuel cycle used in the study was defined as starting with mining and ending with the generation of wastes requiring disposal. Specific disposal environments required technology specifications and repository designs beyond the scope of the study.
- For the list of fuel cycle options to be comprehensive in terms of fuel cycle performance, the EST identified options based on the fundamental physics principles that determine fuel cycle performance, not on choices for technology or implementation. The study considered the possible range for each physics principle, such as thermal, intermediate, or fast neutron spectrum. All combinations of the resulting possibilities for the physics principles resulted in the comprehensive set.
- Fuel cycle options with similar physics-based performance for the benefit criteria and metrics (e.g., waste generation and resource use) were collected into groups called Evaluation Groups, and the

resulting evaluation and screening process was applied to each group of fuel cycle options. Even though fuel cycles had similar physics-based performance, the fuel cycles within each Evaluation Group span a range of overall performance. To appropriately inform on the potential of each group, the EST identified the Metric Data bin (with a range of performance, as discussed below) representing the best performance potential for each Evaluation Group and each evaluation metric.

The fuel cycle options considered in the study were to be as comprehensive as possible with respect to potential fuel cycle performance. As part of the process of developing a comprehensive set of fuel cycles, a survey was conducted to identify any potential constraints that may exist on the types of fuel cycles that could be considered in this study, with the result that all fuel cycles were potentially usable in the US [3]. The permutations of the functional characteristics resulted in 4,398 potentially viable Fuel Cycle Option Groups. The EST combined many of these groups into larger groups using a series of operations based on the similarity of their expected physics-based performance with respect to the evaluation metrics for the benefit criteria. At the end of this process, 40 groups of fuel cycles, or Evaluation Groups, were defined that were sufficient to comprehensively represent all fuel cycle options to inform on their potential for providing substantial improvement: 8 once-through Evaluation Groups, 10 limited recycle Evaluation Groups, and 22 continuous recycle Evaluation Groups. Part of the process was the collection of fuel cycles with similar physics-based performance into 40 Evaluation Groups that maintained the comprehensive nature of the set with regards to performance, although it was also recognized that some of the collected fuel cycles in each Evaluation Group may be relatively poorer performers overall when compared to the best fuel cycles in the group. Table I describes the 40 Evaluation Groups in more detail.

Determination of the Metric Data required detailed information about fuel cycle performance. To support the development of the Metric Data, an Analysis Example was identified for each Evaluation Group by specifying the irradiation environment and fuel type for the Fuel Cycle Option Group. For example, a PWR irradiation environment using uranium oxide fuel as the thermal reactor in a fuel cycle was identified since this level of detail was necessary to obtain accurate information on the effects of irradiation on fuel resource needs, nuclear fuel composition, and SNF characteristics. The Analysis Example was only used for calculating detailed reactor physics-based material mass balance information and other necessary information that provided an initial estimate of the performance of the Evaluation Group. For this Evaluation and Screening, the EST specifically chose the Analysis Examples to reflect a wide variety of possible irradiation systems to convey the broad scope of the Evaluation and Screening, not knowing a priori if the selected irradiation system represented the best performing system for each Evaluation Group. The EST performed the Evaluation and Screening on the Evaluation Groups, not on the Analysis Examples or their Fuel Cycle Option Group.

For each metric, the EST divided the potential range of the data into a small number of bins, with each bin covering a part of the entire data range. Using the results provided by an Analysis Example, the EST identified the bin containing that information as the initial determination of the Metric Data for that Evaluation Group. The EST then considered all of the Fuel Cycle Option Groups within the Evaluation Group to determine if the bin identified for each metric represented the potential performance of the best options within that Evaluation Group. In almost all cases, there was no need to make any changes from this initial determination.

METRIC ANALYSIS

Mass of SNF+HLW per Energy Generated

The mass of SNF and SNF+HLW is defined as the initial heavy metal mass minus any masses recycled in the fuel cycle option or the heavy metal masses (DU, RU, and RTh). Based on this definition, the mass of

SNF+HLW includes the discharged fuel (DF) that is directly disposed, non-recycled heavy metals (except for DU, RU, and RTh), non-recycled fission products, and process losses. Bins determined for the mass of

TABLE I. The 40 Evaluation Groups

Evaluation Group	**Short Description Indicative of Fuel Cycles in the Evaluation Group**
Once-through	
EG01	Once-through using enriched-U fuel in thermal critical reactors
EG02	Once-through using enriched-U fuel to high burnup in thermal or fast critical reactors
EG03	Once-through using natural-U fuel in thermal critical reactors
EG04	Once-through using natural-U fuel to very high burnup in fast critical reactors
EG05	Once-through using enriched-U/Th fuel in thermal or fast critical reactors
EG06	Once-through using Th fuel to very high burnup in thermal externally-driven systems (EDS)
EG07	Once-through using natural-U fuel to very high burnup in thermal or fast EDS
EG08	Once-through using Th fuel to very high burnup in fast EDS
Limited Recycle	
EG09	Limited recycle of U/TRU with new natural-U fuel to very high burnup in fast critical reactors
EG10	Limited recycle of ^{233}U/Th with new Th fuel in fast and/or thermal critical reactors
EG11	Limited recycle of ^{233}U/Th with new enriched-U/Th fuel in fast or thermal critical reactors
EG12	Limited recycle of U/Pu with new natural-U fuel in fast and/or thermal critical reactors
EG13	Limited recycle of U/Pu with new enriched-U fuel in thermal critical reactors
EG14	Limited recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors
EG15	Limited recycle of U/Pu with new enriched-U fuel in both fast and thermal critical reactors
EG16	Limited recycle of U/Pu with new enriched-U fuel in thermal critical reactors and fast EDS
EG17	Limited recycle of Pu/Th with new enriched-U/Th fuel in thermal critical reactors
EG18	Limited recycle of ^{233}U/Th with new enriched-U/Th fuel in thermal critical reactors
Continuous Recycle	
EG19	Continuous recycle of U/Pu with new natural-U fuel in thermal critical reactors
EG20	Continuous recycle of U/TRU with new natural-U fuel in thermal critical reactors
EG21	Continuous recycle of U/Pu with new enriched-U fuel in thermal critical reactors
EG22	Continuous recycle of U/TRU with new enriched-U fuel in thermal critical reactors
EG23	Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors
EG24	Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors
EG25	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in thermal critical reactors
EG26	Continuous recycle of ^{233}U/Th with new Th fuel in thermal critical reactors
EG27	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in fast critical reactors
EG28	Continuous recycle of ^{233}U/Th with new Th fuel in fast critical reactors
EG29	Continuous recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors
EG30	Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors
EG31	Continuous recycle of U/Pu with new enriched-U fuel in both fast and thermal critical reactors
EG32	Continuous recycle of U/TRU with new enriched-U fuel in both fast and thermal critical reactors
EG33	Continuous recycle of U/Pu with new natural-U fuel in both fast EDS and thermal critical reactors
EG34	Continuous recycle of U/TRU with new natural-U fuel in both fast EDS and thermal critical reactors
EG35	Continuous recycle of U/Pu with new enriched-U fuel in both thermal critical reactors and fast EDS
EG36	Continuous recycle of U/TRU with new enriched-U fuel in both thermal critical reactors and fast EDS
EG37	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in both fast and thermal critical reactors
EG38	Continuous recycle of ^{233}U/Th with new Th fuel in both fast and thermal critical reactors

Evaluation Group	Short Description Indicative of Fuel Cycles in the Evaluation Group
EG39	Continuous recycle of ^{233}U/Th with new enriched-U fuel in both thermal critical reactors and fast EDS
EG40	Continuous recycle of ^{233}U/Th with new Th fuel in fast EDS and thermal critical reactors

Note: EDS = externally driven systems (subcritical reactors)

SNF+HLW metric— ranging from A (highest performance bin) to F (lowest performance bin)—are presented in Table II.

TABLE II. Metric Bins for Mass of SNF+HLW Disposed per Energy Generated

Bin ID	Data Range (t/GWe-yr)	Bin Description
A	< 1.65	Mass of SNF+HLW disposed per energy generated < 1.65 t/GWe-yr; 1.65 t/GWe-yr is approximately the HLW mass that would result from processing of LWR SNF to separate and recover all uranium
B	1.65 to < 3	Mass of SNF+HLW disposed per energy generated from 1.65 t/GWe-yr to < 3 t/GWe-yr
C	3 to < 6	Mass of SNF+HLW disposed per energy generated from 3 t/GWe-yr to < 6 t/GWe-yr
D	6 to < 12	Mass of SNF+HLW disposed per energy generated from 6 t/GWe-yr to < 12 t/GWe-yr
E	12 to < 36	Mass of SNF+HLW disposed per energy generated from 12 t/GWe-yr to < 36 t/GWe-yr; contains the Basis of Comparison (EG01)
F	≥ 36	Mass of SNF+HLW disposed per energy generated equals or greater than 36 t/GWe-yr

The final Metric Data for the 40 Evaluation Groups are plotted in Fig. 2, with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

The Evaluation Group EG01, the Basis of Comparison, is in bin E because its Analysis Example has a mass of SNF+HLW of ~22 t/GWe-yr. If the level of improvement represented by bin A were considered significant, then the corresponding set of Evaluation Groups meeting or exceeding that level of improvement is listed as promising. Those Evaluation Groups include:

Bin A: *< 1.65 t/GWe-yr*	*EG06, EG07, EG08, EG16, EG21, EG22, EG23, EG24, EG25, EG26, EG28, EG29, EG30, EG31, EG32, EG33, EG34, EG35, EG36, EG37, EG39, EG40*

If the level of improvement represented by bin B is also considered to be significant, then the promising Evaluation Groups that would be added to those in bin A would include:

Bin B: 1.65 to < 3 t/GWe-yr	*EG09, EG15, EG19, EG20, EG27, EG38*

The mid-point masses for these two bins indicate a factor of about 10 or more reduction in the mass of SNF+HLW relative to that of bin E, which contains EG01.

Note that of the Evaluation Groups in bins A and B—EG06, EG07, and EG08—are once-through fuel cycle systems using externally-driven subcritical irradiation systems (ADS and FFH systems). These three Evaluation Groups are in bin A because it was assumed that a high fuel burnup of 75% would be attainable using the externally driven systems, leading to the low mass of SNF+HLW estimated for those groups.

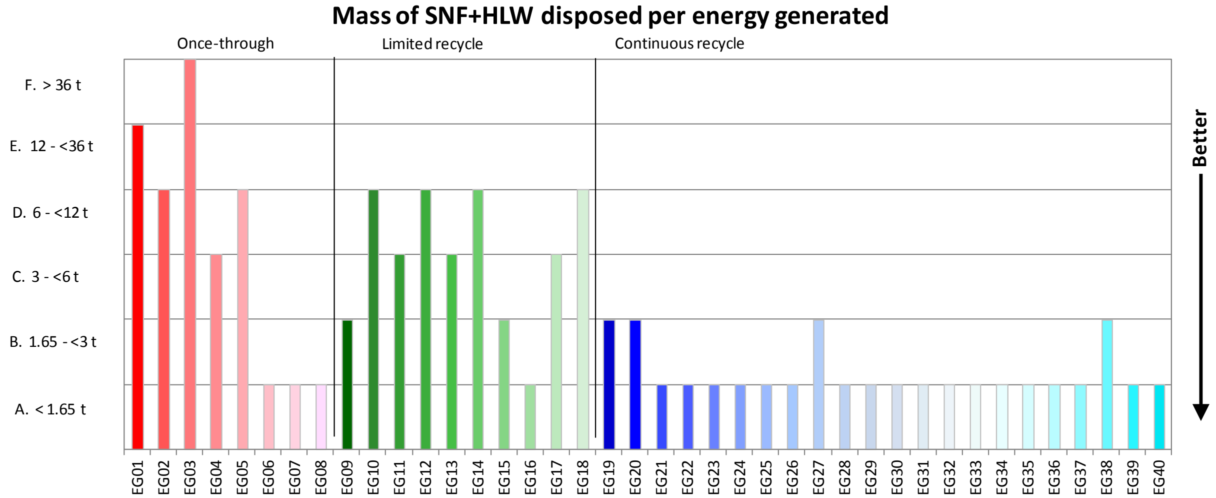


Fig 2. Metric Data for Mass of SNF+HLW Disposed per Energy Generated for the 40 Evaluation Groups ordered by Evaluation Group Number.

With the exception of EG06, EG07, and EG08, all the other members of bins A and B are Evaluation Groups involving the reprocessing of SNF. Of these other members, only EG09, EG15 and EG16 involve systems with the limited-recycle fuel cycle strategy.

If the level of improvement represented by bin C is also considered to be significant, then the promising Evaluation Groups that would be added to those in bins A and B would include:

Bin C: 3 to < 6 t/GWe-yr *EG04, EG11, EG13, EG17*

Comparing bin mid-points, bin C provides a factor of 5 reduction in mass of SNF+HLW relative to bin E. The Analysis Example for EG04 is a fast-spectrum system in which only DU is used as input fuel feed material in the full-cycle equilibrium state. This is a once-through system that also assumes that a relatively high burnup can be achieved. The Evaluation Groups EG11, EG13, and EG17 involve limited recycle options in which SNF is finally disposed.

If the level of improvement represented by bin D is also considered to be significant, then the promising Evaluation Groups that would be added to those in bins A, B and C would include:

Bin D: 6 to < 12t/GWe-yr *EG02, EG05, EG10, EG12, EG14, EG18*

Comparing bin mid-points, bin D provides a factor of 2 reduction in mass of SNF+HLW relative to bin E.

The Analysis Examples for EG02 and EG05 involve the use of high burnup fuels (more than a factor of two higher than that of the basis of comparison, but lower than for those in bin A to C). EG10, EG12, EG14, and EG15 involve limited recycle options in which SNF is finally disposed.

Activity of SNF+HLW at 100 years per Energy Generated

The SNF+HLW radioactivity (activity) value at 100 years after discharge is used as a metric for the Nuclear Waste Management Criterion. The final Metric Data for the 40 Evaluation Groups are provided in Fig. 3, with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

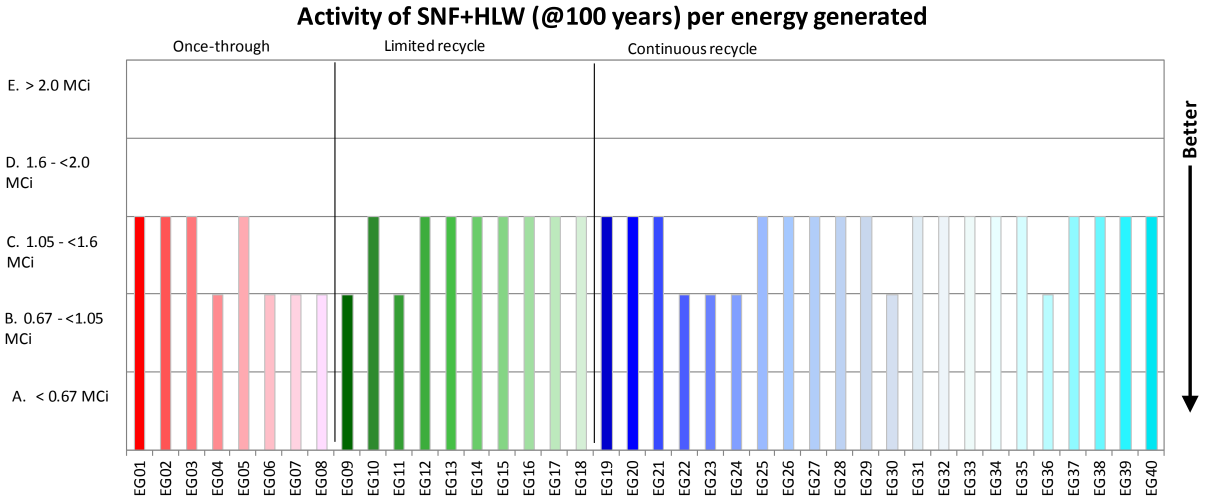


Fig. 3. Metric Data for Activity of SNF+HLW at 100 Years per Energy Generated for the 40 Evaluation Groups ordered by Evaluation Group Number.

The Evaluation Group EG01, the Basis of Comparison, is in bin C (the activity of SNF+HLW per energy generated is 1.34 MCi/GWe-yr). No Analysis Example provides a 50% reduction in the activity of SNF+HLW relative to that of EG01 over all the 40 Evaluation Groups; hence, there is no Evaluation Group in bin A. Additionally, no Evaluation Groups are in bins D and E. If the level of improvement represented by bin B was considered significant, then the corresponding set of Evaluation Groups meeting or exceeding that level of improvement is listed as promising. Those Evaluation Groups include:

Bin B: *0.67 to < 1.05 MCi/GWe-yr*	*EG04, EG06, EG07, EG08, EG09, EG11, EG22, EG23, EG24, EG30, EG36*

The once-through options represented by EG04, EG06, EG07, and EG08, are in bin B, because the long residence time of fuel in the externally driven system helps the reduction of the content of the high activity nuclides at time of fuel discharge. The other Evaluation Groups, EG09 and EG11, are limited recycle cases, and EG22 to EG36 are continuous recycle cases. The limited recycle cases, EG09 and EG11, also benefit from the long residence time of the fuel in the reactor. The common feature of the continuous recycle options (EG22, EG23, EG24, EG30, and EG36) is that they involve the recycle of all the transuranic elements with the exception of EG23. In this regard, it is noted that not all of the continuous recycle options with recycle of the transuranic elements are on this list. For example, options EG20, EG32, and EG34 are not on the list; they are, however, among the better performing options in bin C.

Activity of SNF+HLW at 100,000 Years per Energy Generated

The binned activity of the SNF+HLW at 100,000 years Metric Data for the 40 Evaluation Groups is provided in Fig. 4 with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

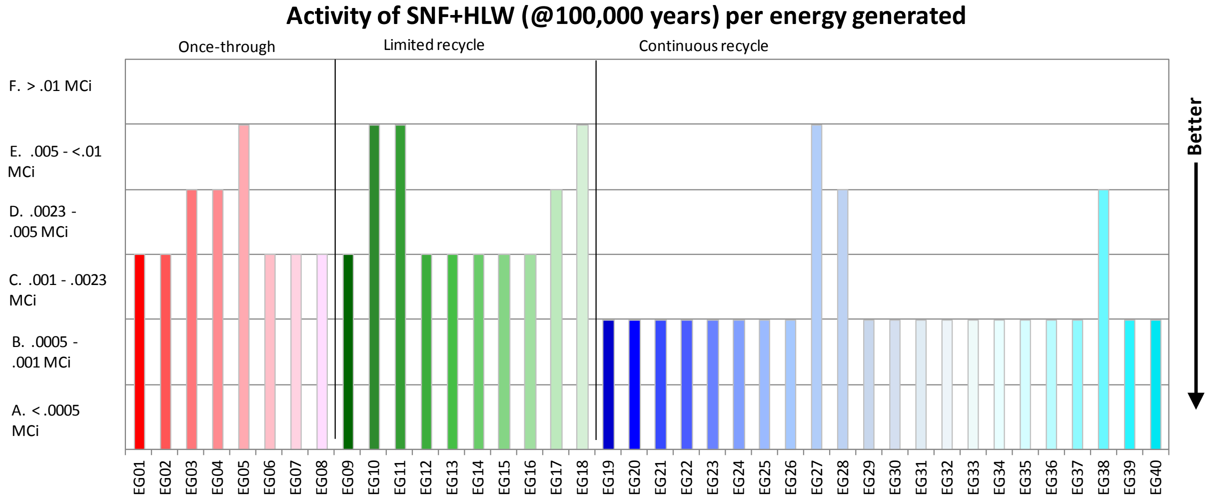


Fig. 4. Metric Data for Activity of SNF+HLW at 100,000 years Disposed per Energy Generated for the 40 Evaluation Groups Ordered by Evaluation Group Number.

The Evaluation Group EG01, the basis of comparison, is in bin C because its Analysis Example has an activity of SNF+HLW at 100,000 years per energy generated value of 1.65 × 10^3 Ci/GWe-yr. Note that no evaluation group is in bin A. Additionally, there are no Evaluation Groups in bin F.

If the level of improvement represented by bin B was considered significant, then the corresponding set of Evaluation Groups meeting or exceeding that level of improvement is listed as promising. Those Evaluation Groups include:

Bin B: 5.0 × 10^{-4} to < 1.0 × 10^{-3} MCi/GWe-yr	*EG19, EG20, EG21, EG22, EG23, EG24, EG25, EG26, EG29, EG30, EG31, EG32, EG33, EG34, EG35, EG36, EG37, EG39, EG40*

The options in bin B are continuous recycle fuel cycle options and most are all uranium systems, with a few thorium-based options. The Evaluation Groups for the continuous-recycle fuel cycles EG27, EG28 and EG38, are not in bin B because thorium fuel is used as feed material in their analysis examples.

Mass of DU+RU+RTh Disposed per Energy Generated

The mass of DU+RU+RTh disposed per energy generated is defined as the sum of DU, RU, and RTh disposed from the fuel cycle option normalized to the energy generated by the option. The final metric bin data for the 40 Evaluation Groups are provided in Fig. 5, with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

The Evaluation Group EG01, the basis of comparison, is in bin E because its Analysis Example has a DU+RU+RTh mass of ~167 t/GWe-yr. If the level of improvement represented by bin A is considered significant, then the corresponding set of Evaluation Groups meeting or exceeding that level of improvement is listed as promising. Those Evaluation Groups include:

Bin A *< 1 t/GWe-yr*	*EG03, EG04, EG06, EG07, EG08, EG09, EG10, EG14, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG38, EG40*

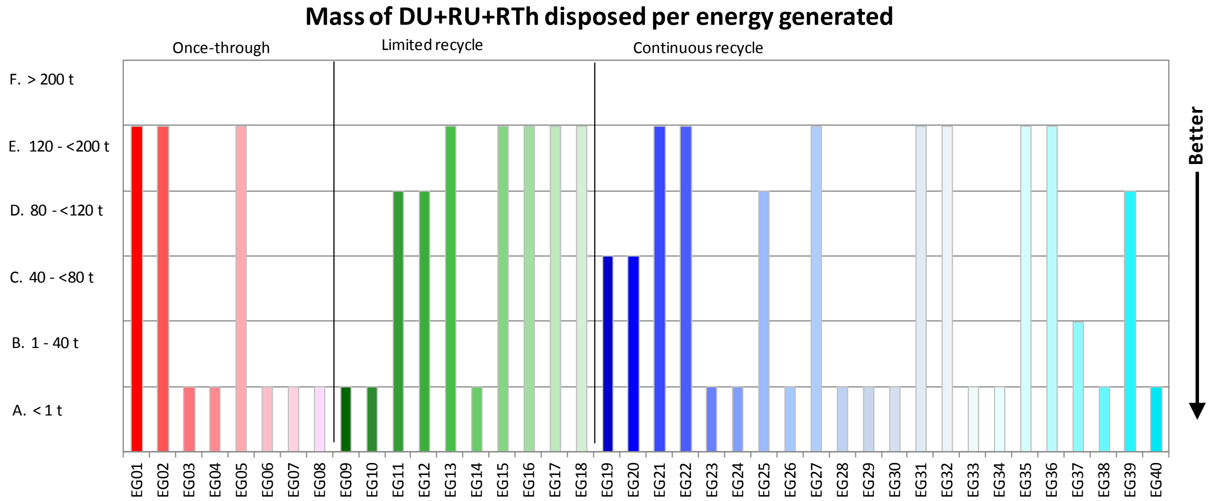


Fig. 5. Metric Data for the Mass of DU+RU+RTH Disposed per Energy Generated for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Comparing bin mid-points, bin A provides over two orders of magnitude reduction in mass of DU+RU+RTh relative to bin E.

This list is comprised of fuel cycle options intended to not use uranium enrichment (EG03, EG04, EG07, EG09, EG14, EG23, EG24, EG29, EG30, EG33, and EG34) or that use thorium-only fuels (EG06, EG08, EG10, EG26, EG28, EG38, and EG40). The set EG03–EG08 is comprised of once-through fuel cycle, the set EG09–EG14 is comprised of limited recycle options, and the set EG23–EG40 is comprised of all continuous recycle options, all with no uranium enrichment requirement as a focus of the Evaluation Group.

If the level of improvement represented by bin B were also considered to be significant, then the promising Evaluation Groups that would be added to those in bin A would include:

Bin B: 1 to < 40 t/GWe-yr *EG37*

Comparing bin mid-points, bin B provides more than a factor of 5 reduction in mass of DU+RU+RTh relative to bin E. The Analysis Example for EG37 is a three-stage Analysis Example and requires enrichment to support only a very small portion of the fuel cycle energy balance (~12% power share for the first stage).

If the level of improvement represented by bin C were also considered significant, then the promising Evaluation Groups that would be added to those in bins A and B would include:

Bin C: 40 to < 80 t/GWe-yr *EG19, EG20*

Comparing bin mid-points, bin C provides more than a factor of 2 reduction in mass of DU+RU+RTh relative to bin E. As mentioned above, EG19 and EG20 do not require enrichment, and their Analysis examples are fuel cycle with uranium continuous recycle in heavy water reactors. They fall in this group because natural uranium is used to replenish the fissile stock and is ultimately recycled after use.
Bin D offers ~1.5 to 2 fold reduction in the mass of DU+RU+RTh (comparing bin mid-points), but this is not typically considered transformational in the mass of material to be disposed.

Volume of LLW per Energy Generated

The final metric bin data for the 40 Evaluation Groups are provided in Fig. 6, with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

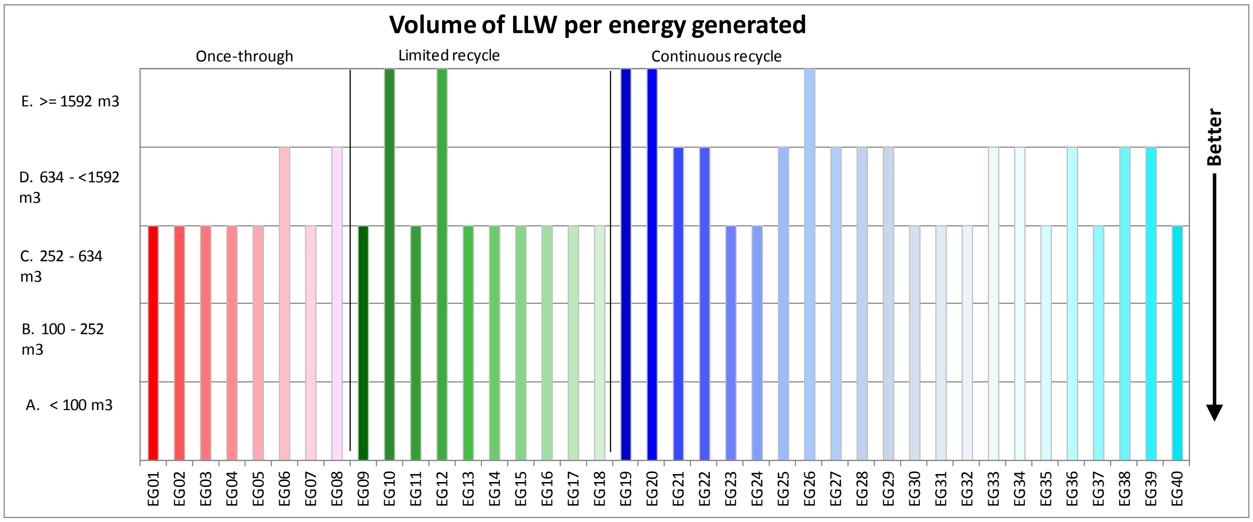


Fig. 6. Metric Data for the volume of LLW per energy generated for the 40 Evaluation Groups by Evaluation Group number.

The Basis of Comparison (EG01) is found in Bin C based on its value of 398.84 m^3 of LLW/GWe-yr. If the level of improvement represented by bin A or B were considered significant, then the corresponding set of Evaluation Groups meeting or exceeding that level of improvement would be considered as promising. However neither of these bins is populated. This means that none of the Evaluation Groups reduced the volume of low-level waste generated by more than 40% from the Basis of Comparison. Bin C contained 22 of the Evaluation Groups, including the Basis of Comparison (EG01). Eight of the 22 continuous recycle Evaluation Groups are contained within bin C. If the Evaluation Groups having LLW generation that is similar to that for the Basis of Comparison are viewed as being promising since LLW generation does not increase with some more complex fuel cycles, then those Evaluation Groups are in bin C, and they include once-through, limited recycle, and continuous recycle options:

Bin C *252 to < 634 m^3/GWe-yr*	*EG01, EG02, EG03, EG04, EG05, EG07, EG09, EG11, EG13, EG14, EG15, EG16, EG17, EG18, EG23, EG24, EG30, EG31, EG32, EG35, EG37, EG40*

ANALYSIS AT THE NUCLEAR WASTE MANAGEMENT CRITERION LEVEL

Moving from the metric level comparison to a criterion level comparison requires that the performance of an Evaluation Group relative to the performance of the Basis of Comparison on all five metrics be considered simultaneously. Table III shows the metric data for all 40 Evaluation Groups on all five metrics.

As observed from Table III, performance improvement with respect to EG01, the Basis of Comparison, is possible for the mass and activity metrics, but not for the volume of LLW. Three Evaluation Groups (EG23, EG24, and EG30 shaded in Table III) are the best performing Evaluation Groups for the Nuclear Waste Management Criterion.

- EG23 - Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors
- EG24 - Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors
- EG30 - Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors

Similar to the discussion of promising groups with respect to each individual metric, the identification of promising groups at the criterion level depends on what level of improvement over the Basis of Comparison is sufficient for a decision-maker to feel that improvement is “significant.” Different decision makers or stakeholders are likely to set that threshold for whether a group is considered “promising” differently, so the results in this section are presented with respect to several different threshold values.

Three thresholds were defined for identifying potentially promising sets of Evaluation Groups with respect to the Nuclear Waste Management criterion. The thresholds were defined by considering the specific improvements for each evaluation metric that were considered as potentially significant, and combining them using a shape functions and metric tradeoff factors to yield a utility. Table IV shows the thresholds and Table V shows the Evaluation Groups that meet each of the thresholds. Rationales for the threshold values and a discussion of the results follow the table.

The “highest achieved benefit utility” threshold is defined by the highest metric bins that were obtained for any Evaluation Group, as shown in the first row of Table IV. Using the shape function and metric tradeoff factors, this threshold is defined by a utility of 0.878 (0.574 higher than the Basis of Comparison). There are three Evaluation Groups that achieve this level of performance:

- EG23 - Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors
- EG24 - Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors
- EG30 - Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors

The Evaluation Groups with the next highest benefit utility had the same metric data for the volume and mass metrics but provided lower benefit for the activity metrics. Considering this observation, Threshold 1 was defined by still considering the highest bins achieved for the mass and volume metrics, but using the next lower bins for activity of SNF+HLW at 100,000 years and at 100 years (equivalent to the metric data for EG01 for those two evaluation metrics). This gives a threshold utility for nuclear waste management of 0.842 (0.538 higher than the Basis of Comparison), and would reflect a view that somewhat less improvement in activity would be acceptable as long as the improvement in waste mass are realized. As shown in Table V, this added Evaluation Groups EG07 and EG40 to the three Evaluation Groups identified above.

- EG07 - Once-through using natural-U fuel to very high burnup in thermal or fast EDS
- EG40 - Continuous recycle of 233U/Th with new Th fuel in fast EDS and thermal critical reactors

Continuing with the logic of setting thresholds based on metric data changes, Threshold 2 was set by using the next lower bins for both of the waste mass metrics in addition to the activity metrics, as listed in Table IV. The corresponding benefit utility is 0.638, 0.334 better than the Basis of Comparison, and it represents a threshold where one bin less reduction in improvement from the highest performing Evaluation Groups would still be considered acceptable, given the reduction in the mass of SNF+HLW is still about an order of magnitude compared to EG01. This added the following Evaluation Groups:

- EG06 - Once-through using Th fuel to very high burnup in thermal EDS
- EG08 - Once-through using Th fuel to very high burnup in fast EDS

TABLE III. Nuclear Waste Management Metric Data

EG	Mass of SNF+HLW Disposed	Activity of SNF+HLW at 100 years	Activity of SNF+HLW at 100,000 years	Mass of DU+RU+RTh Disposed	Volume of Low Level Waste
EG01	Bin E	Bin C	Bin C	Bin E	Bin C
EG02	Bin D	Bin C	Bin C	Bin E	Bin C
EG03	Bin F	Bin C	Bin D	Bin A	Bin C
EG04	Bin C	Bin B	Bin D	Bin A	Bin C
EG05	Bin D	Bin C	Bin E	Bin E	Bin C
EG06	Bin A	Bin B	Bin C	Bin A	Bin D
EG07	Bin A	Bin B	Bin C	Bin A	Bin C
EG08	Bin A	Bin B	Bin C	Bin A	Bin D
EG09	Bin B	Bin B	Bin C	Bin A	Bin C
EG10	Bin D	Bin C	Bin E	Bin A	Bin E
EG11	Bin C	Bin B	Bin E	Bin D	Bin C
EG12	Bin D	Bin C	Bin C	Bin D	Bin E
EG13	Bin C	Bin C	Bin C	Bin E	Bin C
EG14	Bin D	Bin C	Bin C	Bin A	Bin C
EG15	Bin B	Bin C	Bin C	Bin E	Bin C
EG16	Bin A	Bin C	Bin C	Bin E	Bin C
EG17	Bin C	Bin C	Bin D	Bin E	Bin C
EG18	Bin D	Bin C	Bin E	Bin E	Bin C
EG19	Bin B	Bin C	Bin B	Bin C	Bin E
EG20	Bin B	Bin C	Bin B	Bin C	Bin E
EG21	Bin A	Bin C	Bin B	Bin E	Bin D
EG22	Bin A	Bin B	Bin B	Bin E	Bin D
EG23	Bin A	Bin B	Bin B	Bin A	Bin C
EG24	Bin A	Bin B	Bin B	Bin A	Bin C
EG25	Bin A	Bin C	Bin B	Bin D	Bin D
EG26	Bin A	Bin C	Bin B	Bin A	Bin E
EG27	Bin B	Bin C	Bin E	Bin E	Bin D
EG28	Bin A	Bin C	Bin D	Bin A	Bin D
EG29	Bin A	Bin C	Bin B	Bin A	Bin D
EG30	Bin A	Bin B	Bin B	Bin A	Bin C
EG31	Bin A	Bin C	Bin B	Bin E	Bin C
EG32	Bin A	Bin C	Bin B	Bin E	Bin C
EG33	Bin A	Bin C	Bin B	Bin A	Bin D
EG34	Bin A	Bin C	Bin B	Bin A	Bin D
EG35	Bin A	Bin C	Bin B	Bin E	Bin C
EG36	Bin A	Bin B	Bin B	Bin E	Bin D
EG37	Bin A	Bin C	Bin B	Bin B	Bin C
EG38	Bin B	Bin C	Bin D	Bin A	Bin D
EG39	Bin A	Bin C	Bin B	Bin D	Bin D
EG40	Bin A	Bin C	Bin B	Bin A	Bin C

- EG09 - Limited recycle of U/TRU with new natural-U fuel to very high burnup in fast critical reactors
- EG16 - Limited recycle of U/Pu with new enriched-U fuel in thermal critical reactors & fast EDS
- EG21 - Continuous recycle of U/Pu with new enriched-U fuel in thermal critical reactors
- EG22 - Continuous recycle of U/TRU with new enriched-U fuel in thermal critical reactors
- EG25 - Continuous recycle of 233U/Th with new enriched-U/Th fuel in thermal critical reactors
- EG26 - Continuous recycle of 233U/Th with new Th fuel in thermal critical reactors
- EG28 - Continuous recycle of 233U/Th with new Th fuel in fast critical reactors
- EG29 - Continuous recycle of U/Pu with new natural-U fuel in both fast & thermal critical reactors

- EG31 - Continuous recycle of U/Pu with new enriched-U fuel in both fast & thermal critical reactors
- EG32 - Continuous recycle of U/TRU with new enriched-U fuel in both fast & thermal critical reactors
- EG33 - Continuous recycle of U/Pu with new natural-U fuel in both fast EDS & thermal critical reactors
- EG34 - Continuous recycle of U/TRU with new natural-U fuel in both fast EDS & thermal critical reactors
- EG35 - Continuous recycle of U/Pu with new enriched-U fuel in both thermal critical reactors & fast EDS
- EG36 - Continuous recycle of U/TRU with new enriched-U fuel in both thermal critical reactors & fast EDS
- EG37 - Continuous recycle of 233U/Th with new enriched-U/Th fuel in both fast & thermal critical reactors
- EG38 - Continuous recycle of 233U/Th with new Th fuel in both fast & thermal critical reactors
- EG39 - Continuous recycle of 233U/Th with new enriched-U fuel in both thermal critical reactors & fast EDS

These are all continuous recycle options except for EG06, EG08, EG09 and EG16. The Evaluation Groups EG06, EG08, and EG09 are in this set because of their very high fuel burnup characteristic.

TABLE IV. Thresholds Considered for Identifying Promising Groups with Respect to the Nuclear Waste Management Criterion

Threshold Type	Mass of SNF+HLW	Activity of SNF+HLW at 100 years	Activity of SNF+HLW at 100,000 years	Mass of DU+RU+RTh	Volume of LLW	Utility Representing NWM
Highest achieved benefit utility	Bin A: < 1.65 t/GWe-yr	Bin B: 0.67 to < 1.05 MCi/GWe-yr	Bin B: 0.0005 to < 0.001 MCi/GWe-yr	Bin A: 1 t/GWe-yr	Bin C: 252 to < 634 m^3/GWe-yr	0.878
Threshold 1 (Utility = 0.842)	Bin A: < 1.65 t/GWe-yr	Bin C: 1.05 to < 1.60 MCi/GWe-yr	Bin C: 0.001 to < 0.0023 MCi/GWe-yr	Bin A: 1 t/GWe-yr	Bin C: 252 to < 634 m^3/GWe-yr	0.842
Threshold 2 (Utility = 0.638)	Bin B: 1.65 to < 3 t/GWe-yr	Bin C: 1.05 to < 1.60 MCi/GWe-yr	Bin C: 0.001 to < 0.0023 MCi/GWe-yr	Bin B: 1 to < 40 t/GWe-yr	Bin C: 252 to < 634 m^3/GWe-yr	0.638
EG01	Bin E: 12 to < 36 t/GWe-yr	Bin C: 1.05 to < 1.60 MCi/GWe-yr	Bin C: 0.001 to < 0.0023 MCi/GWe-yr	Bin E: 120 to < 200 t/GWe-yr	Bin C: 252 to < 634 m^3/GWe-yr	0.304

Note: Initial shape functions and tradeoff factor set were used to define this numeric threshold. The blue shading is used to indicate which bin data have been relaxed in going from one threshold to the next threshold.

TABLE V. Nuclear Waste Management Criterion Results Based on Thresholds

Threshold Type	Evaluation Groups At or Above Threshold
Highest achieved benefit utility	EG23, EG24, EG30
Threshold 1	EG07, EG23, EG24, EG30, EG40
Threshold 2	EG06, EG07, EG08, EG09, EG16, EG21, EG22, EG23, EG24, EG25, EG26, EG28, EG29, EG30, EG31, EG32, EG33, EG34, EG35, EG36, EG37, EG38, EG39, EG40

CONCLUSIONS

The EST evaluated and screened nuclear fuel cycles *only* at what is termed the "functional" level, using the fundamental physics characteristics of each step in a fuel cycle (i.e., the physics principles defining *what* happens at each fuel cycle step, not the technologies for *how* it is accomplished) both to enable creation of a comprehensive set and to provide flexibility for future R&D directions into specific technology choices. The EST identified several promising Evaluation Groups that have the potential for improved performance relative to the current US fuel cycle.

If ***only considering the nuclear waste management criteria*** it was shown that on a per unit energy generated basis, reductions in generation of fuel cycle wastes requiring geologic disposal by as much as a factor of 10 or more, reductions in long-term activity corresponding to a reduction in long-term radiation hazard by as much as a factor of 10 or more, and reduction in uranium (depleted from the enrichment process or recovered from reprocessing) and/or thorium (recovered from reprocessing) disposal needs by a factor of 100 or more were possible with similar low-level waste generation.

It was also observed that:

- The use of uranium enrichment in an option generally adversely affected (degraded) performance of the option under this criterion.
- Some continuous recycle options not requiring enrichment consistently performed well (e.g., EG23, EG24, EG29, EG30, EG33, EG34, and EG40 always appeared) independent of the 6 combinations of shape functions and tradeoff functions considered.
- Once-through fuel cycle options with very high burnup thorium or uranium fuels generally performed well under this criterion (EG04, EG06, EG07, EG08 for example).
- The use of thorium feed fuel affects adversely the activity metrics (particularly at 100,000 years) and tends to degrade somewhat the performance of the options utilizing thorium feed. The fact that some of the Th/U fuel options require enrichment did not help performance.
- In general, once-through and limited recycle options with relatively low burnup primarily had the lowest performance, along with the Basis of Comparison (EG01).
- Options with continuous recycle of uranium in a thermal-reactor spectrum (represented with heavy water reactor) did not particularly do well because a large natural uranium feed is required to provide the fissile U-235 for such options (some insufficient plutonium is produced and recycled).

These results support separations R&D for advanced fuel cycles, advanced fuels and advanced fast reactors.

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