APPENDIX E

EVALUATION CRITERIA RESULTS

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E. EVALUATION CRITERION RESULTS

This appendix discusses the results for the Evaluation Criteria using the metric data from Appendix D, along with the shape functions to provide metric utility and the metric tradeoff factors for combining metric utilities to obtain the utility for each criterion. Where appropriate, sensitivity studies are performed to inform on the effects of different perspectives on the value of a change in each metric and on the relative importance of each metric for each criterion.

Content and Structure of Appendix E:

This appendix contains the Evaluation and Screening results for each Evaluation Criterion individually, in the same order the criteria are discussed in the main report. Where appropriate, the shape functions and metric tradeoff factors for the Evaluation Metrics are described. These functions and tradeoff factors are used to translate the metric data (described in Appendix D) into a "utility" representing the overall value of each Evaluation Group with respect to the Criterion, following the process described in Appendix A. For four of the benefit criteria (Nuclear Waste Management, Safety, Environmental Impact, and Resource Utilization) several analyses were conducted and are described in each subsection.

- A plot showing position of each Evaluation Group on a benefit versus challenge graph (see Figure E.1). On this plot, the utility representing the benefit of each Evaluation Group is calculated using one set of shape functions and metric tradeoff factors. This utility is plotted on the y-axis. The x-axis plots the challenge for each Evaluation Group, where challenge is represented by the utility for the Development and Deployment Risk Criterion, again using one set of shape functions and metric tradeoff factors. This analysis and associated plot gives an indication of which Evaluation Groups have the potential for improvement, reflected by a benefit utility greater than that for the Basis of Comparison (EG01), and how challenging it will be to achieve that utility, reflected by a challenge utility lower than that for EG01. This analysis and plot is presented only for four of the benefit criteria.
- One or more sets of promising Evaluation Groups may be identified based on the potential for "significant improvement." Because a "significant" improvement is a matter of perspective, these results are expressed as a conditional, i.e., if a given level of improvement were considered significant, then the corresponding set of Evaluation Groups meeting or exceeding that level of improvement is identified as promising. To identify these potentially promising Evaluation Groups, utility "threshold(s)" are identified based on the underlying improvement for each of the supporting Evaluation Metrics, as described in Appendix D. All Evaluation Groups above a threshold are identified as promising groups for a decision-maker who determines that the line represents sufficient improvement.
- For criteria where potentially promising sets of Evaluation Groups are identified, a ranking is presented that considers both the increased benefit and the challenge of achieving that greater benefit. This ranking is based on the ratio of incremental benefit to incremental challenge for each Evaluation Group in the promising set, where "incremental" is defined by the difference in performance (on the utility scale representing benefit and on the utility scale representing challenge) between the Evaluation Group and the basis of comparison (EG01). Conceptually, this is the ranking that would be produced if a vertical line was drawn through EG01 on the graph and that line is "swept" to the left while remaining anchored at EG01. Only Evaluation Groups that are in the promising set (above the "threshold" line in the figure) are ranked, eliminating options that show only marginal promise over the Basis of Comparison.

The last section in this Appendix, E-10, contains the EST expert opinions on what may be considered as a significant improvement for each Evaluation Criterion and the underlying Evaluation Metrics. This information was requested by DOE-NE as additional input from the EST.

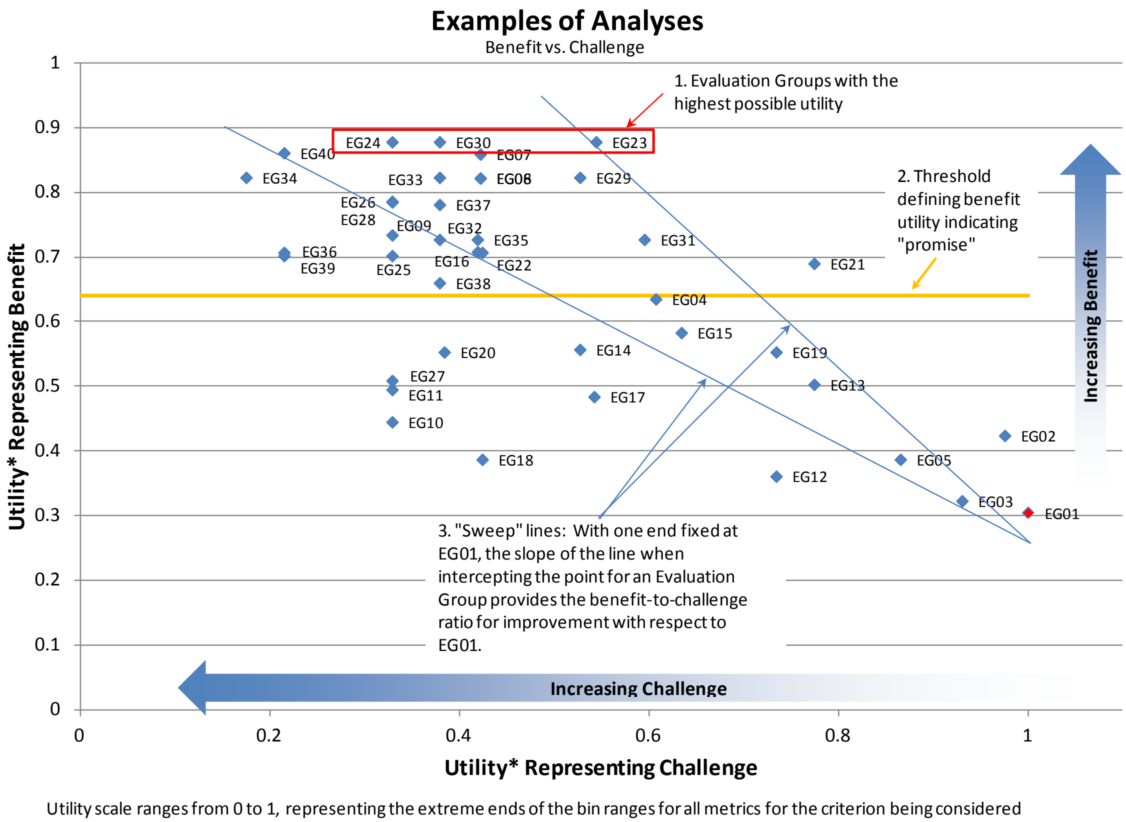

Figure E.1. Interpreting the Benefit Utility versus Challenge Utility Plot for an Evaluation Criterion.

Finally, some tables in this report list the Evaluation Groups with a color coding scheme (e.g., Table E-1.7). This is to aid in identifying trends amongst the Evaluation Groups. The color scheme has 3 sets of colors with different gradation of shading: shades of red to pink for Once-Through options (EG01 to EG08), shades of green for Limited Recycle options (EG09 to EG18), and shades of blue for Continuous Recycle options (EG19 to EG40), as shown in Figure E.2.

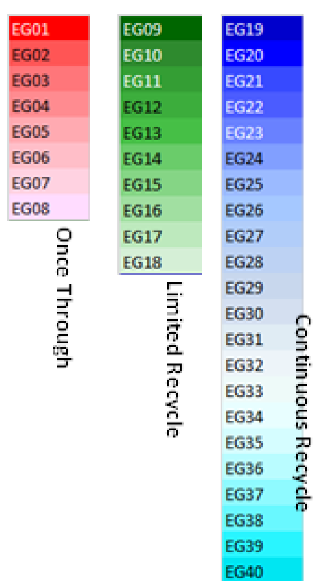

Figure E.2. Evaluation Group Color Coding.

E-1. Nuclear Waste Management Criterion

Review of Metric Data for Nuclear Waste Management Criterion

Five Evaluation Metrics were identified as informing on the Nuclear Waste Management Criterion.

- Mass of SNF+HLW disposed per energy generated
- Activity of SNF+HLW (@100 years) per energy generated
    - Radiation for handling, shielding, and disposal can be derived
    - Decay heat for disposal can be derived
- Activity of SNF+HLW (@100,000 years) per energy generated
    - Radiotoxicity of disposed materials that could be released from the repository can be derived
- Mass of DU+RU+RTh disposed per energy generated
- Volume of LLW per energy generated

Moving from the metric level comparison (described in Appendix D) 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 E-1.1 and Figure E-1.1 show the metric data for all 40 Evaluation Groups on all five metrics.

Table E-1.1. 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

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
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

Note: The Metric Bin descriptions and data ranges for the Nuclear Waste Management Metrics are given in Appendix C.

As discussed in Appendix D, and as observed from Table E-1.1, 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 E-1.1) 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

The metric data for these Evaluation Groups are represented by the green line in Figure E-1.1; the metric data for the basis of comparison (EG01) is represented by the red line. The grey lines represent the metric data for other Evaluation Groups. Any ranking or comparison of these (non-dominant) groups is a matter of perspective: whether one Evaluation Group is "better" than another with respect to Nuclear Waste Management depends on the relative importance one attaches to the differences between bins for each metric, and on the relative importance of differences across the metrics. As described in Appendix A, these perspectives are represented in this Evaluation and Screening study by *shape functions* and *metric tradeoff factors*. The three dominant Evaluation Groups will always rank at the top of any comparative list for this criterion, regardless of the perspectives, because they outperform the other groups based on the metric data directly.

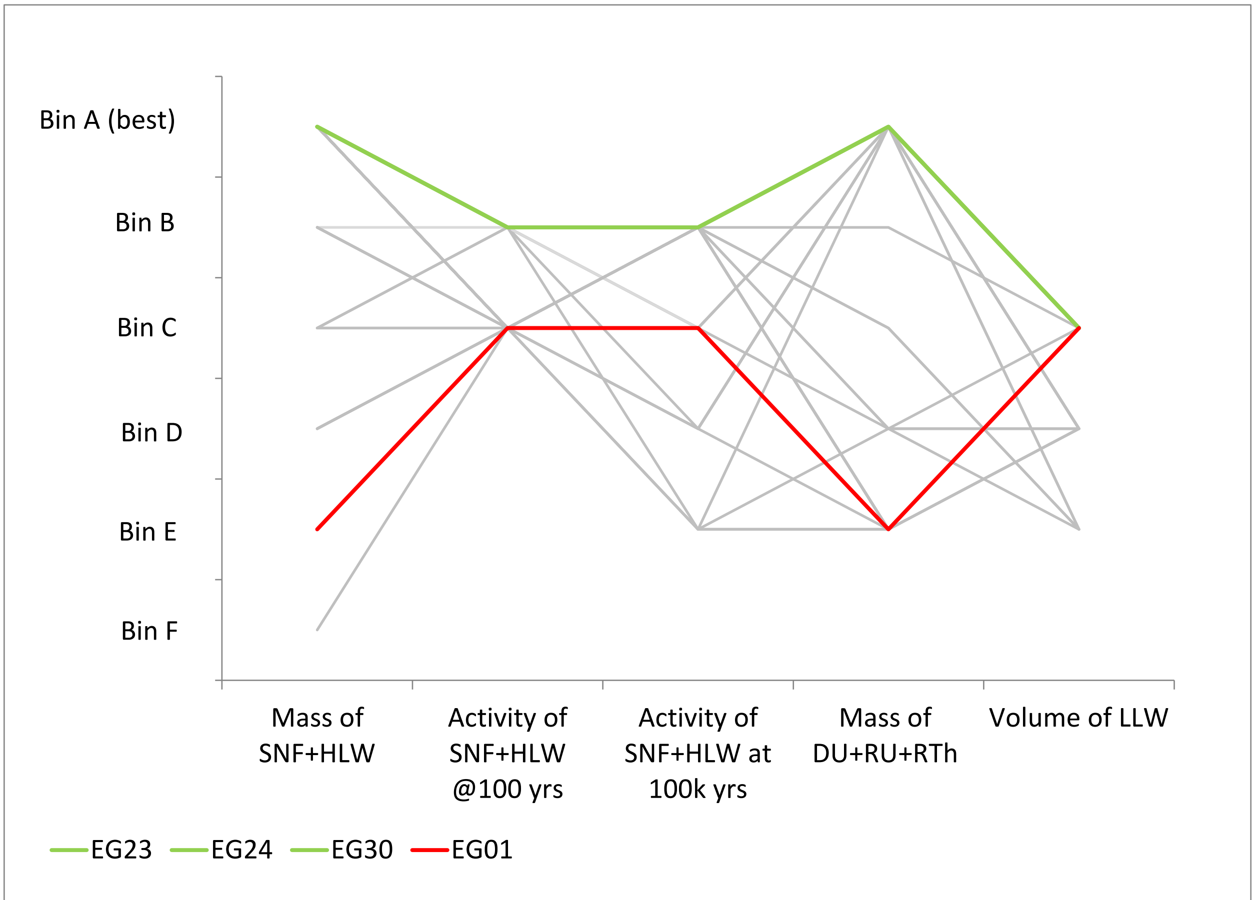

Figure E-1.1. Metric data for 40 Evaluation Groups on the Five Nuclear Waste Management Metrics.

E-1.1 Shape Functions and Metric Tradeoff Factors for Nuclear Waste Management

Shape functions represent the relative importance of changes or differences in the metric data for a single metric, and metric tradeoff factors reflect the relative importance of changes in one metric versus changes in the others. Different perspectives on the importance of these changes are possible. This evaluation and screening deliberately considers a range of possible perspectives in the criterion-level evaluations (as well as in the evaluations to be presented in Appendix F that consider multiple criteria). The goals of considering these multiple perspectives are two-fold: first is to identify any Evaluation Groups that perform well and might be considered promising under a variety of different perspectives, and second is to identify and be able to call out any Evaluation Group that might perform well under only one or a few perspectives. The first group might be considered the “robust” high performers, while the second group highlights Evaluation Groups that might best meet a particular set of interests or needs.

The shape functions defined for the five Evaluation Metrics for Nuclear Waste Management are described in Table E-1.2 and are illustrated in Figures E-1.2 to E-1.6.

Table E-1.2. Shape Functions for Nuclear Waste Management Metrics.

Mass of SNF+HLW: One perspective evaluated
Shape Function 1 is logarithmic in mass, reflecting the perspective that an order of magnitude change in the mass of SNF+HLW is important for determining the nature of nuclear waste management challenge (that has not yet been resolved).
Activity of SNF+HLW at 100 years: Two perspectives evaluated
Shape Function 1 is linear in activity, reflecting a perspective that every unit reduction in activity at 100 years is equally important for disposal design and operational issues.
Shape Function 2 is logarithmic in activity, reflecting a perspective that the disposal design and operational challenges are proportional to orders of magnitude differences in activity at 100 years.
Activity of SNF+HLW at 100,000 years: One perspective evaluated
Shape Function 1 is logarithmic in activity, reflecting a perspective that an order of magnitude change in the activity of SNF+HLW at 100,000 years is important for determining the nature of nuclear waste isolation challenge (that has not yet been resolved).
Mass of DU+RU+RTh: Two perspectives evaluated
Shape Function 1 is logarithmic in mass, reflecting a perspective that an order of magnitude change in the mass of DU+RU+RTh is important for determining the nature of DU+RU+RTh disposal challenge. This perspective is similar that associated with the shape function for the mass of SNF+HLW, and suggests that the nature of the DU+RU+RTh disposal challenge is yet to be resolved.
Shape Function 2 is linear in mass, reflecting a perspective that every unit change in the mass of DU+RU+RTh amount is equally important. This is consistent with a view that DU+RU+RTh disposal can be considered as a commoditized market.
Volume of Low Level Waste (LLW): Two perspectives evaluated
Shape Function 1 is logarithmic in volume, reflecting a perspective that an order of magnitude change in the volume of low level waste is important to ensure drastic reduction in the volume of LLW. This is captured by a logarithmic function.
Shape Function 2 is linear in volume, reflecting a perspective that every unit change in the low level waste amount is equally important. This is consistent with a view that the volume of low level can be considered as a commoditized market.

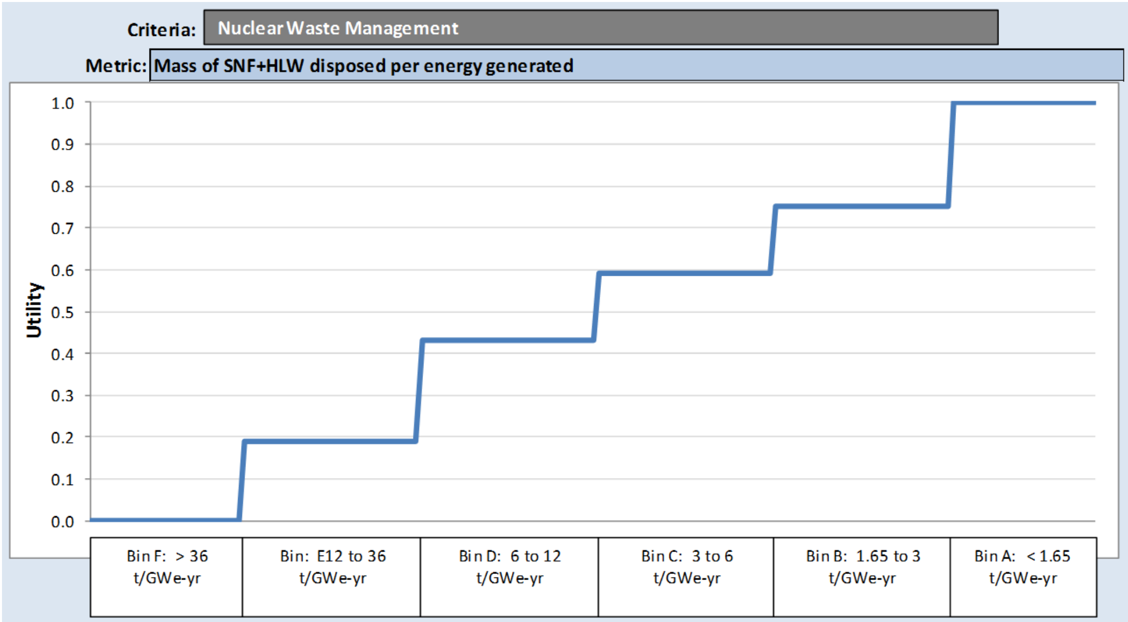

Figure E-1.2. Shape Function 1 for Mass of SNF+HLW Disposed per Energy Generated.

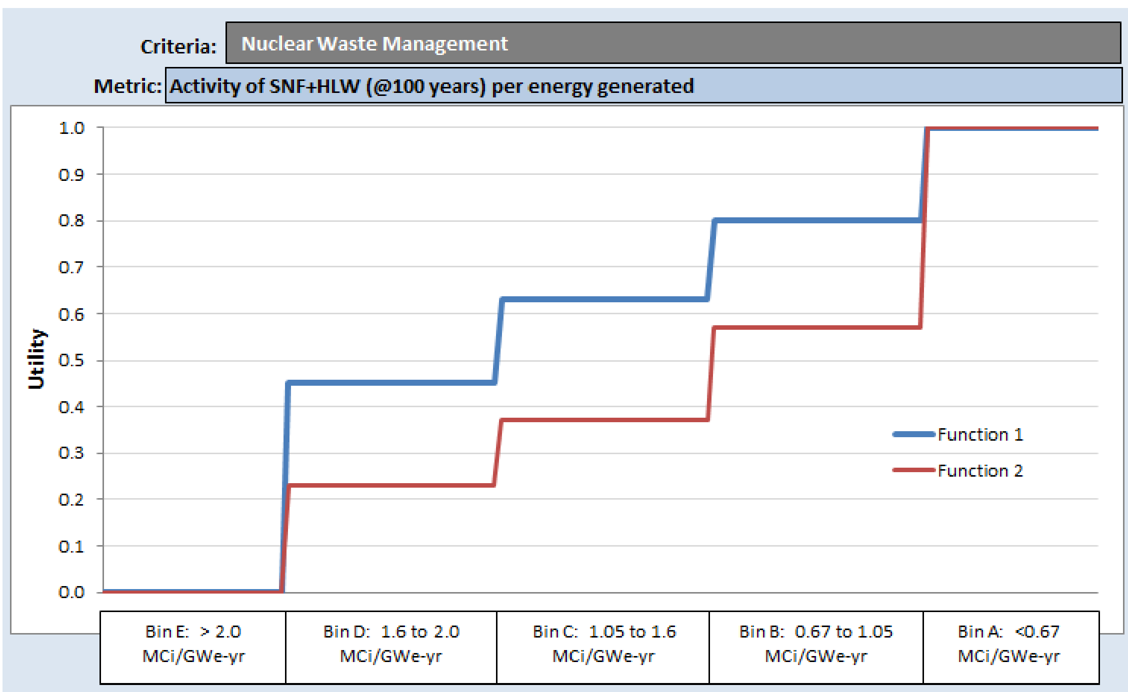

Figure E-1.3. Shape Function 1 for Activity of SNF + HLW at 100 years per Energy Generated.

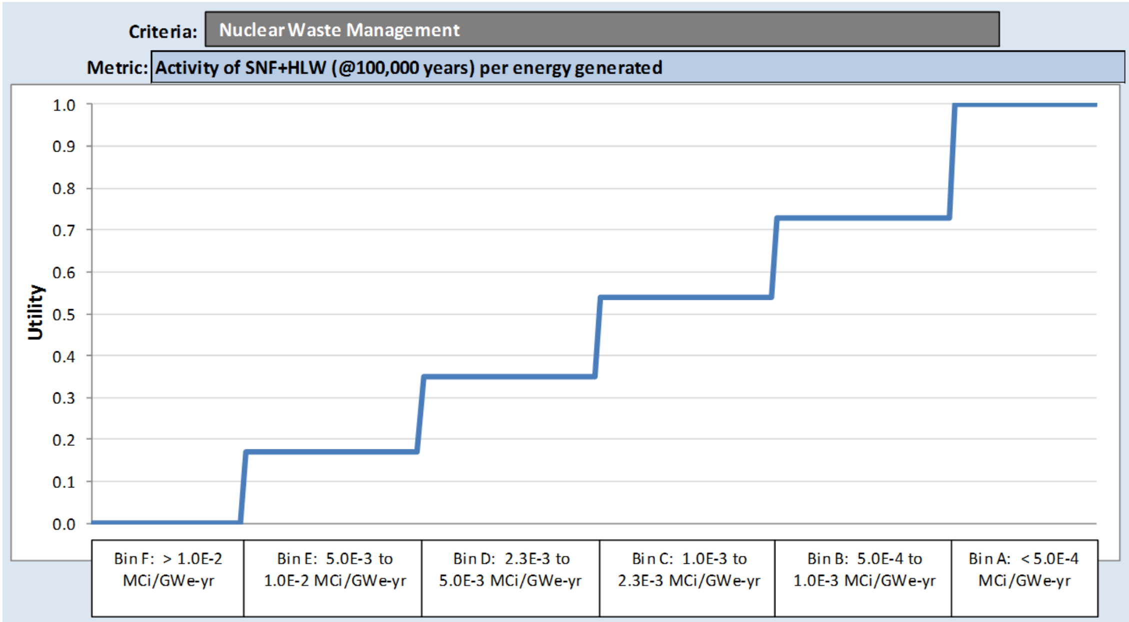

Figure E-1.4. Shape Function 1 for Activity of SNF + HLW at 100,000 years per Energy Generated.

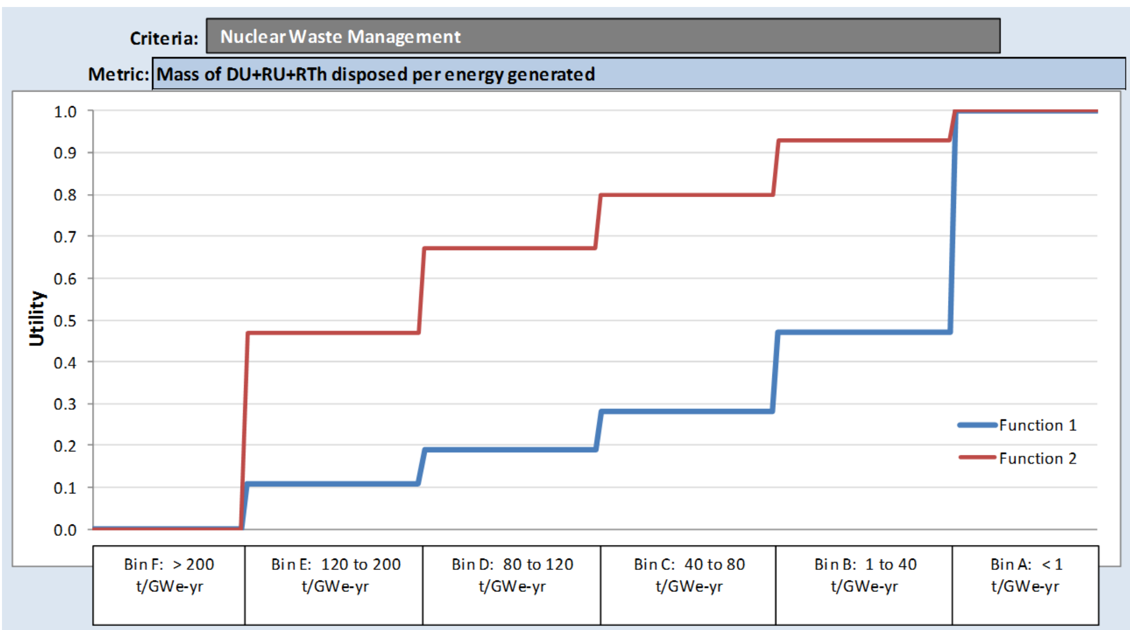

Figure E-1.5. Shape Functions 1 and 2 for Mass of DU+RU+RTh Disposed per Energy Generated.

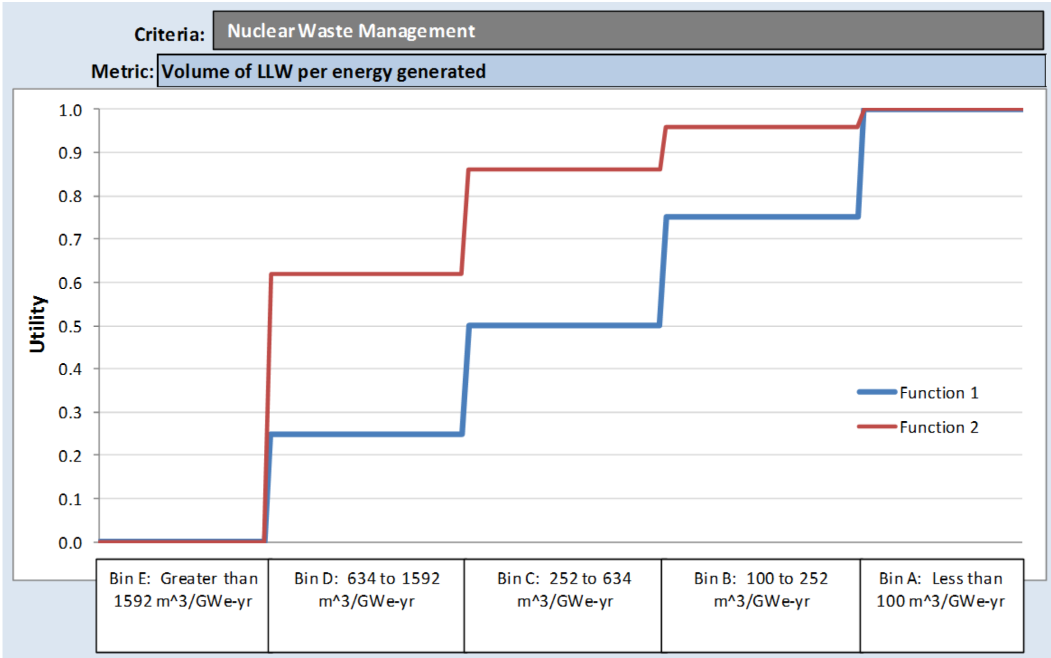

Figure E-1.6. Shape Functions 1 and 2 for Volume of LLW per Energy Generated.

Three sets of metric tradeoff factors were defined to explore different perspectives on the relative importance of differences between metrics. Table E-1.3 provides a summary of the metric tradeoff factors considered. The metric tradeoff factors represent the relative importance of changes in each Evaluation Metric, where "changes" are defined by the full range of the bin structure. The three sets of metric tradeoff factors reflect the following considerations:

Set 1: Explore an emphasis on the long-term isolation challenge of SNF and HLW by emphasizing the importance of changes in the activity of SNF+HLW at 100,000 years.

Set 2: Explore emphasis on reducing the quantity of SNF+HLW that must be disposed, as represented by the mass.

Set 3: Explore roughly equal emphasis on improving performance in each of the three waste streams (SNF+HLW, DU+RU+RTh and LLW).

Table E-1.3. Tradeoff Factors for Nuclear Waste Management Metrics.

	Metric tradeoff factors representing the relative importance of changes in each metric, considering the entire range defined by the bins for each metric		
Metric	**Set 1**	**Set 2**	**Set 3**
Mass of SNF+HLW	0.20	0.50	0.10
Activity of SNF+HLW at 100 years	0.15	0.10	0.10
Activity of SNF+HLW at 100,000 years	0.50	0.10	0.10
Mass of DU+RU+RTh	0.10	0.15	0.35
Volume of LLW	0.05	0.15	0.35

Note: All metrics are normalized per energy generated.

In calculating and presenting criterion-level and scenario-level (see Appendix F-2) analyses, it is convenient to choose an initial perspective (one set of shape functions and one metric tradeoff factor set) to illustrate the types of analyses that were conducted and to describe a set of results, followed by an exploration of whether and how those results change under different shape functions and metric tradeoff factors. For the Nuclear Waste Management Criterion, those analyses were conducted using Shape Function 1 for all Evaluation Metrics, and using metric Tradeoff Factor set 2, which emphasizes the value of reducing the mass of SNF+HLW.

Insights on Promising Options for the Nuclear Waste Management

The results obtained with the initial set of shape functions and tradeoff factors are discussed in this section. Sensitivity analyses considering six different combinations of shape functions and tradeoff factors are provided in Section E-1.2.

Similar to the discussion of promising groups with respect to each individual metric in Appendix D, 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.

Benefit and challenge results are shown in Figure E-1.7.

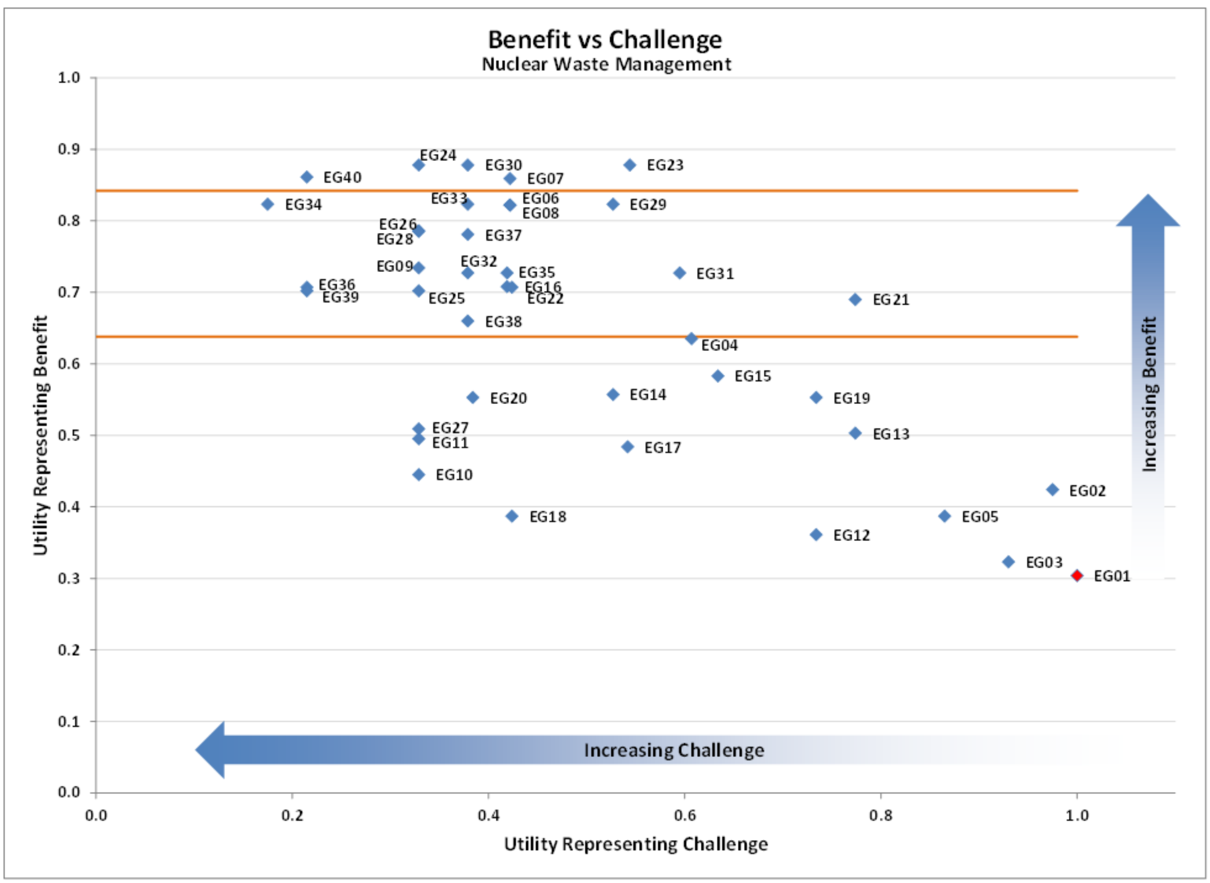

Figure E-1.7. Benefit versus Challenge of Each Evaluation Group Considering the Nuclear Waste Management Criterion.

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 in Appendix D, and combining them using the initial shape functions and metric tradeoff factors to yield a utility. Table E-1.4 shows the thresholds and Table E-1.5 shows the Evaluation Groups that meet each of the thresholds. Rationales for the threshold values and a discussion of the results follow the table.

Table E-1.4. 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 has been relaxed in going from one threshold to the next threshold.

Table E-1.5. 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

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 E-1.4. Using the initial shape functions and metric tradeoff factors, this threshold is defined by a utility of 0.878 (0.574 higher than the Basis of Comparison). As discussed in the review of the metric data above, there are three Evaluation Groups (EGs) 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 E-1.5 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 ^{233}U/Th with new Th fuel in fast EDS and thermal critical reactors

Continuing with the logic of setting thresholds based on the 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 E-1.4. The corresponding benefit utility is 0.638, 0.334 better than the Basis of Comparison, and represents a threshold where one bin less reduction in improvement from the highest performing Evaluation Groups would still be considered acceptable, given that 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
- 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 and 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 ^{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
- 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
- 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
- EG39 - Continuous recycle of ^{233}U/Th with new enriched-U fuel in both thermal critical reactors and fast EDS

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

As noted above, the Evaluation Groups that meet each threshold were ranked using the ratio of incremental benefit (the increase in nuclear waste management utility for the Evaluation Group over the nuclear waste management utility for the Basis of Comparison) to incremental challenge as an indication of promise. The ordered lists of Evaluation Groups based on this ratio are summarized in Table E-1.6 for each of the three thresholds defined above, providing one approach for differentiating between the Evaluation Groups within the set defined by each threshold.

Table E-1.6. Nuclear Waste Management Criterion Results Based on Consideration for Benefit-to-Challenge Ratio.

Highest Achieved Utility Ordering (Utility = 0.878)		**Threshold 1 Ordering (Utility = 0.842)**		**Threshold 2 Ordering (Utility = 0.638)**	
Evaluation Group	Ratio	Evaluation Group	Ratio	Evaluation Group	Ratio
EG23	1.259	EG23	1.259	EG21	1.708
EG30	0.924	EG07	0.960	EG23	1.259
EG24	0.855	EG30	0.924	EG29	1.097
		EG24	0.855	EG31	1.044
		EG40	0.710	EG07	0.960
				EG30	0.924
				EG06	0.896
				EG08	0.896
				EG24	0.855
				EG33	0.836
				EG37	0.768
				EG35	0.728
				EG26	0.718
				EG28	0.717
				EG40	0.710
				EG22	0.700
				EG16	0.695
				EG32	0.681
				EG09	0.641
				EG34	0.629
				EG25	0.593
				EG38	0.573
				EG36	0.513
				EG39	0.507

E-1.2 Sensitivity Analysis

There are 24 unique combinations of shape functions and metric tradeoff factors that were considered in evaluating and ranking Evaluation Groups on the Nuclear Waste Management Criterion. The combinations were examined for logical consistency, and exploratory analyses were conducted to reduce this set (if possible) to a smaller set that would still capture any significant differences between ranking and evaluation results. This led to three simplifications:

- It was determined that a combination of a linear shape function for the Mass of DU+RU+RTh and a logarithmic shape function for the Volume of LLW was logically inconsistent: that would represent a situation in which issues related to DU+RU+RTh disposal can be considered solved or commoditized, while LLW disposal issues are yet to be resolved.

- Exploratory analyses showed that there were negligible differences in results associated with the two shape functions for Activity of SNF+HLW at 100 years, so only one of the two needed to be retained in further analyses.

- Exploratory analyses also showed that the results considering a combination of logarithmic shape function for the Mass of DU+RU+RTh with a linear shape function for the Volume of LLW always lay between the results combining either the log shape functions or linear shape function, and thus the bounding sets should be sufficient for exploring the implications of the results.

These simplifications reduced the number of combinations required to represent the range of perspectives on Nuclear Waste Management from 24 to 6 (two combinations of shape functions for the Mass of DU+RU+RTh combined with 3 metric tradeoff factor sets).

The resulting data for the 6 combinations are shown in Figure E-1.8 and Table E-1.7. The figure shows the calculated utility value on the Nuclear Waste Criterion considering all five metrics, using the shape functions and metric tradeoff factors specified; the table shows the same values, with the Evaluation Groups sorted by utility value for each set of shape functions and metric tradeoff factors. The utility scale ranges from 0 to 1, across the range of bins for all five metrics: an Evaluation Group would have to be in the best performing bin on all five metrics to have a Nuclear Waste Management utility value of 1, and would have to be in the worst performing bin on all five metrics to have a utility value of 0.

Several results are apparent:

- Seven Evaluation Groups are highly ranked (they are in the top 10) under all perspectives. These robust high performing groups are EG23, EG24, EG30, EG29, EG33, EG34 and EG40. These are all continuous recycle options.

- Evaluation Groups EG23, EG24, EG30, and EG40 are the most highly ranked Evaluation Groups under all perspectives. As noted above, EG23, EG24, and EG30 dominate all other Evaluation Groups based on their metric data, so this result was expected. These are three continuous recycle Evaluation Groups that involve the recycle of Pu or TRU in critical reactors. EG40 is a continuous recycle EG that involves the recycle of U-233 and requires no uranium enrichment support.

- The basis of comparison, EG01, is always in the bottom 10 of the 40 Evaluation Groups, and when metric Tradeoff Factor set 2 (emphasizing the importance of reducing the mass of SNF+HLW more than the other metrics) is considered, it at the bottom of the list.

- EG07, a once-through fuel cycle option, performs well (ranks highly) under two of the metric tradeoff factor sets, but performs less well under metric Tradeoff Factor set 1, which emphasizes improvements in the metric for Activity of SNF+HLW at 100,000 years.
- EG06 and EG08 perform well under metric Tradeoff Factor set 2, which emphasizes improvements in the metric for the Mass of SNF+HLW, but performs less well under the other two metric tradeoff factor sets.
- EG09, EG04, and EG14 perform well only under metric Tradeoff Factor set 3, which places more emphasis on improvements in the Mass of DU+RU+RTh and the Volume of LLW produced than do the other metric tradeoff sets.
- EG22 performs better under metric Tradeoff Factor set 1, emphasizing improvements in the Activity of SNF+HLW at 100,000 year, but only reaches the top 10 for one set of shape functions.

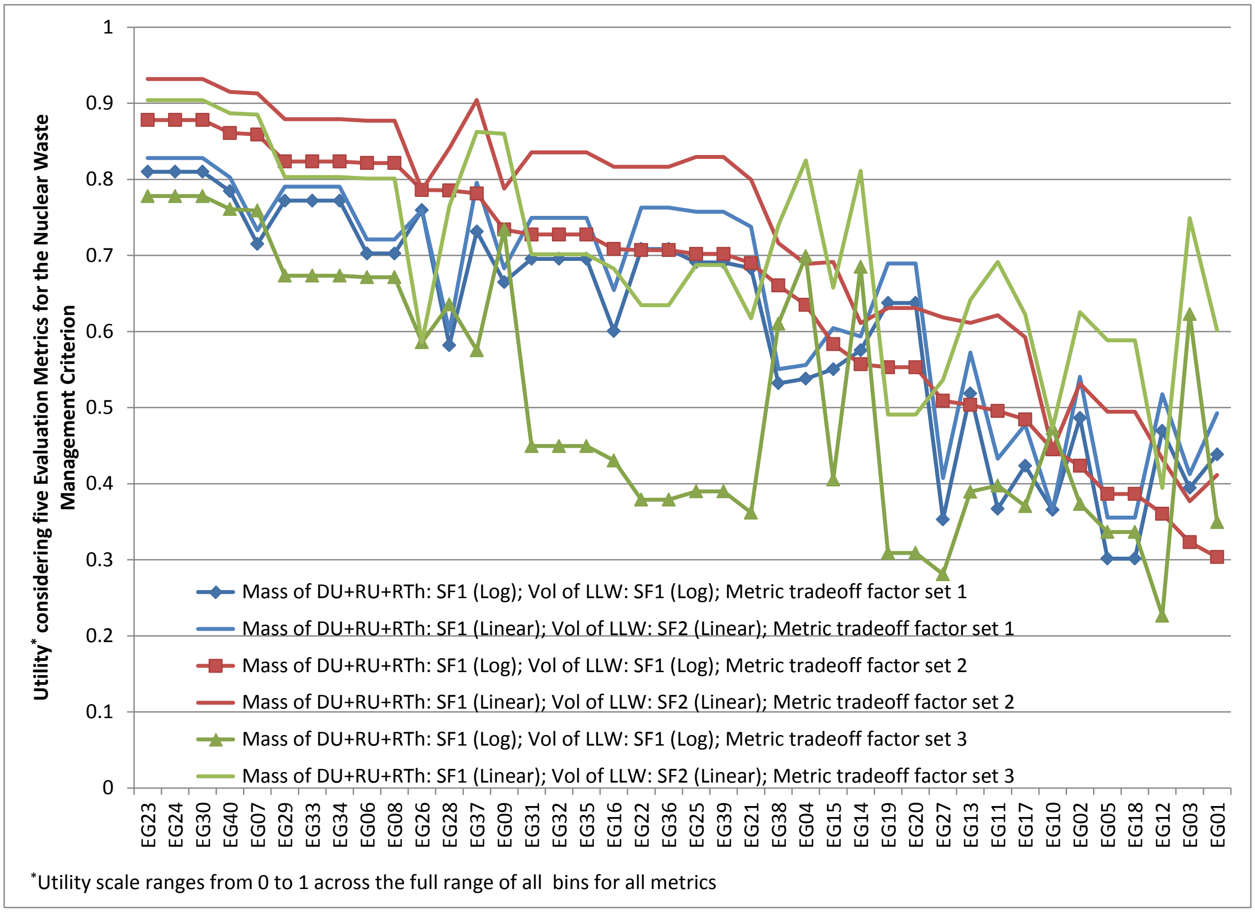

Figure E-1.8. Nuclear Waste Management Criterion Results for Each Evaluation Group, with Different Shape Functions and Trade-off Factors.

Table E-1.7. Ranking of Evaluation Groups by Calculated Utility for the Nuclear Waste Management Criterion, with Different Shape Functions and Trade-off Factors.

Shape function for Mass of DU+RU+RTh	1 (log)		1 (linear)		1 (log)		1 (linear)		1 (log)		1 (linear)	
Shape function for Volumen of LLW	1 (log)		1 (linear)		1 (log)		1 (linear)		1 (log)		1 (linear)	
Metric tradeoff factor set	1		1		2		2		3		3	
	EG23	0.81	EG23	0.828	EG23	0.878	EG23	0.932	EG23	0.778	EG23	0.904
	EG24	0.81	EG24	0.828	EG24	0.878	EG24	0.932	EG24	0.778	EG24	0.904
	EG30	0.81	EG30	0.828	EG30	0.878	EG30	0.932	EG30	0.778	EG30	0.904
	EG40	0.7845	EG40	0.8025	EG40	0.861	EG40	0.915	EG40	0.761	EG40	0.887
	EG29	0.772	EG37	0.7955	EG07	0.859	EG07	0.913	EG07	0.759	EG07	0.885
	EG33	0.772	EG29	0.7905	EG29	0.8235	EG37	0.9045	EG09	0.734	EG37	0.8625
	EG34	0.772	EG33	0.7905	EG33	0.8235	EG29	0.879	EG04	0.699	EG09	0.86
	EG26	0.7595	EG34	0.7905	EG34	0.8235	EG33	0.879	EG14	0.685	EG04	0.825
	EG37	0.7315	EG22	0.763	EG06	0.8215	EG34	0.879	EG29	0.6735	EG14	0.811
	EG07	0.715	EG36	0.763	EG08	0.8215	EG06	0.877	EG33	0.6735	EG29	0.803
	EG22	0.7085	EG26	0.7595	EG26	0.786	EG08	0.877	EG34	0.6735	EG33	0.803
	EG36	0.7085	EG25	0.7575	EG28	0.7855	EG28	0.841	EG06	0.6715	EG34	0.803
	EG06	0.7025	EG39	0.7575	EG37	0.7815	EG31	0.8355	EG08	0.6715	EG06	0.801
	EG08	0.7025	EG31	0.7495	EG09	0.734	EG32	0.8355	EG28	0.6355	EG08	0.801
	EG31	0.6955	EG32	0.7495	EG31	0.7275	EG35	0.8355	EG03	0.623	EG28	0.765
	EG32	0.6955	EG35	0.7495	EG32	0.7275	EG25	0.8295	EG38	0.6105	EG03	0.749
	EG35	0.6955	EG21	0.7375	EG35	0.7275	EG39	0.8295	EG26	0.586	EG38	0.74
	EG25	0.691	EG07	0.733	EG16	0.7085	EG16	0.8165	EG37	0.5755	EG31	0.7015
	EG39	0.691	EG06	0.721	EG22	0.707	EG22	0.8165	EG10	0.473	EG32	0.7015
	EG21	0.683	EG08	0.721	EG36	0.707	EG36	0.8165	EG31	0.4495	EG35	0.7015
	EG09	0.665	EG19	0.6895	EG25	0.702	EG21	0.7995	EG32	0.4495	EG11	0.6915
	EG19	0.6375	EG20	0.6895	EG39	0.702	EG09	0.788	EG35	0.4495	EG25	0.6875
	EG20	0.6375	EG09	0.683	EG21	0.69	EG26	0.786	EG16	0.4305	EG39	0.6875
	EG16	0.6005	EG16	0.6545	EG38	0.6605	EG38	0.716	EG15	0.4055	EG16	0.6825
	EG28	0.582	EG15	0.6045	EG04	0.635	EG15	0.6915	EG11	0.3975	EG15	0.6575
	EG14	0.5755	EG28	0.6005	EG15	0.5835	EG04	0.689	EG25	0.39	EG13	0.6415
	EG15	0.5505	EG14	0.5935	EG14	0.557	EG19	0.631	EG39	0.39	EG22	0.6345
	EG04	0.538	EG13	0.5725	EG19	0.553	EG20	0.631	EG13	0.3895	EG36	0.6345
	EG38	0.532	EG04	0.556	EG20	0.553	EG11	0.6215	EG22	0.379	EG02	0.6255
	EG13	0.5185	EG38	0.5505	EG27	0.509	EG27	0.6185	EG36	0.379	EG17	0.6225
	EG02	0.4865	EG02	0.5405	EG13	0.5035	EG13	0.6115	EG02	0.3735	EG21	0.6175
	EG12	0.4695	EG12	0.5175	EG11	0.4955	EG14	0.611	EG17	0.3705	EG01	0.6015
	EG01	0.4385	EG01	0.4925	EG17	0.4845	EG17	0.5925	EG21	0.362	EG05	0.5885
	EG17	0.4235	EG17	0.4775	EG10	0.445	EG02	0.5315	EG01	0.3495	EG18	0.5885
	EG03	0.3945	EG11	0.433	EG02	0.4235	EG05	0.4945	EG05	0.3365	EG26	0.586
	EG11	0.367	EG03	0.4125	EG05	0.3865	EG18	0.4945	EG18	0.3365	EG27	0.5365
	EG10	0.3655	EG27	0.4075	EG18	0.3865	EG10	0.445	EG19	0.309	EG19	0.491
	EG27	0.353	EG10	0.3655	EG12	0.3605	EG12	0.4325	EG20	0.309	EG20	0.491
	EG05	0.3015	EG05	0.3555	EG03	0.323	EG01	0.4115	EG27	0.281	EG10	0.473
	EG18	0.3015	EG18	0.3555	EG01	0.3035	EG03	0.377	EG12	0.2265	EG12	0.3945

E-1.3 Summary: Characteristics of Promising Groups

From these results it is 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 HWR) 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).

Potential Supporting R&D Indicated by Results for Nuclear Waste Management Criterion

Based on the identified Evaluation Groups above, arising from the conditional statements on promising options, following are the R&D activities that have been identified:

- Separation technologies for the limited and continuous recycle options
- Extremely high burnup fuels (>30%) required for options with no enrichment and no fuel separations
  - Primarily, advanced cladding materials that can withstand high irradiation levels at reactor temperatures
  - Fuel that can retain or safely release fission products from high burnup fuels
- Recycle fuels
- Advanced reactors
  - Fast-spectrum reactor and liquid fuel reactor (e.g., MSR) options
  - Reactor systems with conversion ratio greater than 1
  - Breed and burn reactor concepts that utilize high burnup fuels
- Externally-driven systems utilizing extremely high burnup fuels
  - For very high burnup with no initial enrichment, fusion-fission hybrid system is desirable for high performance.
- Thorium mining, milling, and fuel processing and preparation technologies to implement options using thorium.

E-2. Proliferation Risk Criterion

The background and evaluation approach for this criterion is described in Appendix C, Section C-2, and the discussion of the evaluation metric on material attractiveness is presented in Appendix D, Section D-2.6. For the purpose of this E&S Study, which is to inform the R&D investment prioritization for the DOE Office of Nuclear Energy, the result for this criterion is that no promising options were identified, and that all of the Evaluation Groups were evaluated as capable of being comparable to the current U.S. fuel cycle at the physics-based functional level as far as material attractiveness is concerned. As a consequence, there is no additional information on this criterion presented here, and this criterion was not included in the multiple criteria evaluations presented in Appendix F.

E-3. Nuclear Material Security Risk Criterion

The background and evaluation approach for this criterion is described in Appendix C, Section C-3, and the discussion of the evaluation metrics of material attractiveness and activity are presented in Appendix D, Sections D-2.6 and D-2.7, respectively. For the purpose of this E&S Study, which is to inform the R&D investment prioritization for the DOE Office of Nuclear Energy, the result for this criterion was that all of the Evaluation Groups were assessed as comparable to the current U.S. fuel cycle at the physics-based functional level as far as material attractiveness for usefulness in INDs is concerned. All Evaluation Groups also contain highly radioactive spent fuel and/or HLW, providing targets with activity comparable to the current U.S. fuel cycle in usefulness for RDDs / REDs. As a consequence, no promising options were identified, no additional information on this criterion is presented here, and this criterion was not included in the multiple criteria evaluations presented in Appendix F.

E-4. Safety Criterion

As discussed in Appendix D, for the purposes of this study, the Safety Criterion focused on the challenges in meeting established safety requirements for nuclear facilities, based on the premise that all commercial nuclear facilities are regulated and must meet such safety requirements. Two metrics are considered:

- Challenges of Addressing Safety Hazards
- Safety of the Deployed System

The Metric Data for this Criterion are presented in Appendix D. The results for the Challenges of Addressing Safety Hazards Metric show that all Evaluation Groups without externally driven systems are in Bin C, "Potentially Similar Challenge", as is the Basis of Comparison (EG01). The Evaluation Groups that contain externally driven systems in the analysis examples, i.e., EG06, EG07, EG08, EG16, EG33, EG34, EG35, EG36, EG39, and EG40, are considered "Potentially More Challenging" than the Basis of Comparison and are in Bin D. As a result, no Evaluation Group ranks higher than the Basis of Comparison (EG01) and 10 Evaluation Groups rank lower.

For the Safety of the Deployed System metric, all 40 Evaluation Groups were determined to be able to be deployed safely and there is no difference between any of the Evaluation Groups for this metric.

E-4.1 Shape Functions for Safety Metrics

As previously discussed, shape functions represent the relative importance of changes and differences in the Metric Data for a single metric. The shape functions can represent specific perspectives about the importance of the changes in metric data, and consideration of multiple shape functions can be used to help understand whether and how those perspectives may affect the evaluation results. Three shape functions representing differing perspectives were considered for the Challenges of Addressing Safety Hazards metric. These shape functions are shown in Figure E-4.1 and correspond to the following perspectives:

Shape Function 1: This shape function represents a perspective that uniformly values reduction in challenges of addressing safety hazards ranging from more challenges to fewer challenges in comparison to the Basis of Comparison.

Shape Function 2: This shape function represents a perspective that assigns relatively low value to reducing the challenges of addressing safety hazards below the level of challenge of the existing fuel cycle (moving from Bin C to Bin A), and assigns relatively high value to reducing challenges that are higher down to the level of challenge of the existing fuel cycle (moving from Bin E to Bin C). It reflects a perspective that making it easier is fine, but making it harder, by adding multiple challenges beyond those already addressed, is much worse.

Shape Function 3: This shape function represents a perspective that assigns relatively high value to reducing the challenges of addressing safety hazards below the level of challenge of the existing fuel cycle, and assigns relative low value to reducing higher challenges down to the same level of challenge as the current fuel cycle.

The second Safety Metric, Safety of the Deployed System, is a "go/no-go" metric, i.e., if an Evaluation Group has Metric Data that indicates that the system cannot be deployed safely, that Evaluation Group would be eliminated from the Evaluation and Screening study, and therefore does not require the definition of shape functions. Similarly, as a go/no-go metric, there are no tradeoffs considered between Safety of the Deployed System and any other Metric. As discussed in Appendix D, all Evaluation Groups were found to be safely deployable.

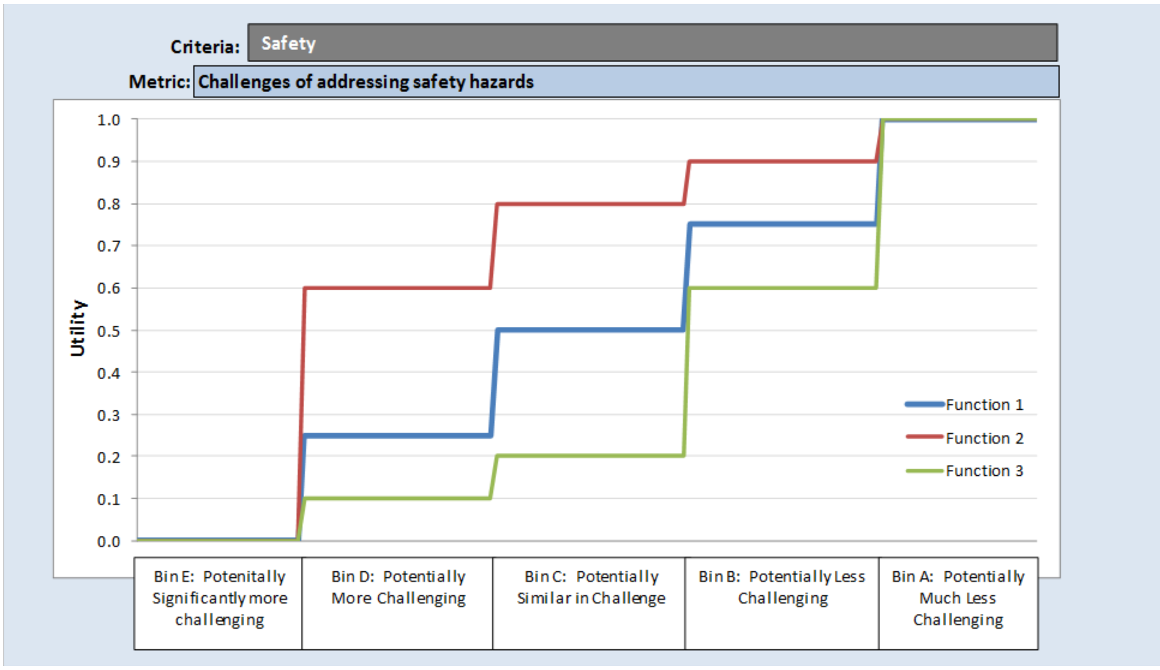

Figure E-4.1. Shape Functions for the Challenges of Addressing Safety Hazards Metric.

E-4.2 Results for the Safety Criterion

Safety at the criterion level is solely determined by the Challenges of Addressing Safety Hazards metric, and there are only two "sets" of Evaluation Groups with respect to that metric: those that have the same level of challenge as the current nuclear fuel cycle (30 of the 40 Evaluation Groups) and those that are potentially more challenging (10 of the 40 Evaluation Groups). The choice of shape function affects the numeric utility representing safety for each Evaluation Group, but does not change the relative ranking of the two sets. For the purpose of displaying results, Shape Function 1 is used. Figure E-4.2 shows the Benefit, here defined by the utility representing Safety on y –axis, and the Challenge, defined by the utility representing the Development and Deployment Risk on the x-axis, for each Evaluation Group. The figure clearly shows the two sets of Evaluation Groups differentiated by their Safety utility.

Observations from these results are as follows:

- All fuel cycle Evaluation Groups except those using EDSs have similar challenges to addressing safety hazards as the Basis of Comparison based on a review of a range of hazard categories and previous industry and research experience with those hazards.
- EDSs have additional challenges that must be addressed associated with the use of the external neutron source and coupling with the blanket system. This includes challenges related to handling large amounts of tritium, worker dose issues related to the operation of the system and coupling between the neutron source and blanket, and safety case for EDSs that operate in subcritical mode including new potential events related to source excursions and reactivity feedback.
- There were no Evaluation Groups that had safety challenges that could not be addressed including the EDSs, which will require additional R&D to address those items identified in the Challenges to Addressing Safety Hazards Metric.

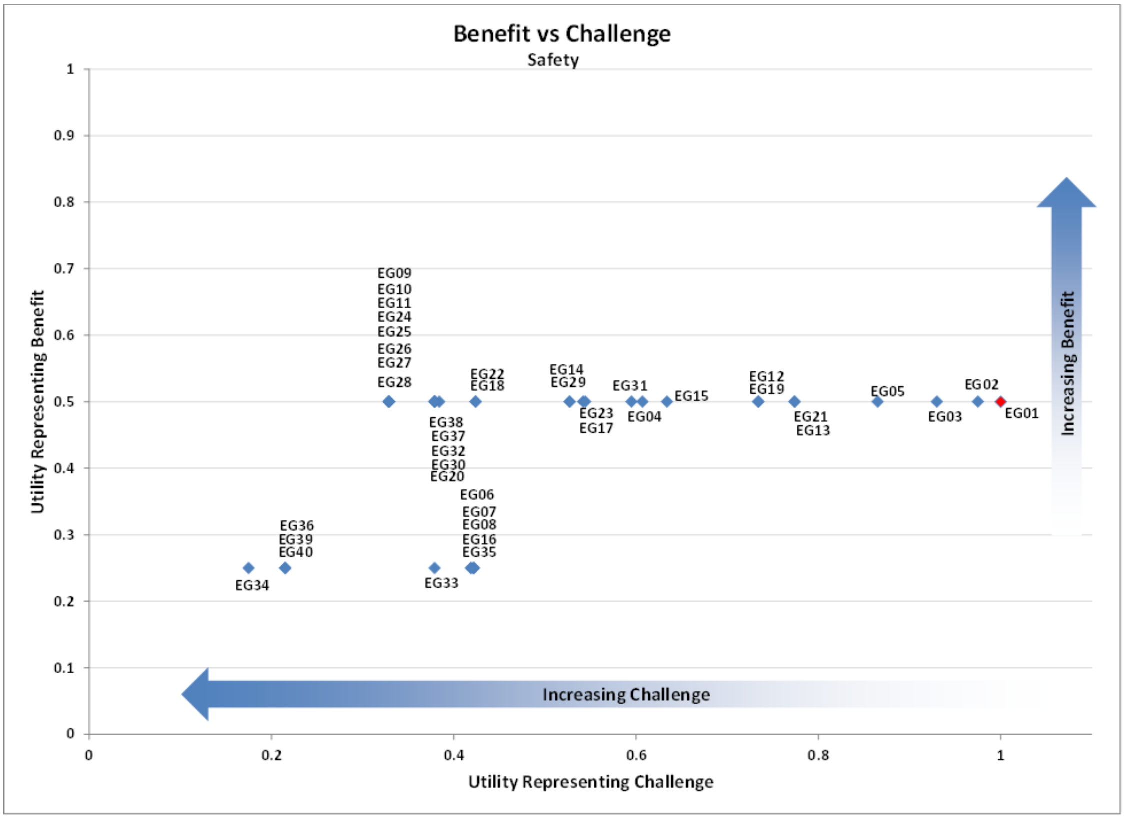

Figure E-4.2. Benefit versus Challenge Results for Benefit Defined by the Safety Criterion Utility.

E-4.3 Promising Evaluation Groups, Supporting R&D, Technical Requirements, and Insights based on the Safety Criterion

No Evaluation Groups rank higher than the Basis of Comparison (EG01) for this criterion and therefore no Evaluation Groups are considered promising with respect to the Safety Criterion. Should those systems that have lower safety utility be identified as promising Evaluation Groups considering other Criteria, there may be a need for research to address the challenges of addressing safety hazards for those systems. The relevant research needs are identified discussed in Appendix C, specifically: operation in sub-critical configurations, challenges in interfacing external neutron sources to fission blankets, and large-scale tritium handling, in cases where FFH technologies are to be considered.

E-5. Environmental Impact Criterion

Four Evaluation Metrics were identified as informing on the Environmental Impact Criterion. Moving from the metric level comparison (described in Appendix D) to a criterion level comparison requires that the performance of an Evaluation Group relative to the performance of the Basis of Comparison on all four metrics be considered simultaneously. Table E-5.1 and Figure E-5.1 show the metric data for all 40 Evaluation Groups on all four metrics.

Seven Evaluation Groups can be identified as "dominant" in terms of the Environmental Impact Criterion, meaning they perform as well or better than any other Evaluation Groups on all four metrics:

- EG04 - Once-through using natural-U fuel to very high burnup in fast critical reactors

- EG09 - Limited recycle of U/TRU with new natural-U fuel to very high burnup in fast critical reactors
- EG14 - Limited recycle of U/Pu with new natural-U fuel in both fast and 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
- EG30 - Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors
- EG40 - Continuous recycle of ^{233}U/Th with new Th fuel in fast EDS and thermal critical reactors

The metric data for these Evaluation Groups are represented by the green line in Figure E-5.1; the metric data for the Basis of Comparison (EG01 - once-through U thermal critical reactor with enrichment) is represented by the red line. The grey lines represent the metric data for other Evaluation Groups.

Any ranking or comparison of the non-dominant groups is a matter of perspective: whether one Evaluation Group is “better” than another with respect to Environmental Impact depends on the relative importance one attaches to the differences between bins for each metric, and on the relative importance of differences across the metrics. As described in Appendix A, these perspectives are represented in the Evaluation and Screening by *shape functions* and *metric tradeoff factors*. The seven dominant Evaluation Groups will always rank at the top of any comparative list, regardless of the perspectives, because they outperform the other groups based on the metric data directly.

Table E-5.1. Environmental Criterion Metric Data.

Evaluation Group	Land Use per Energy Generated	Water Use per Energy Generated	Carbon Emission – CO_2 released per Energy Generated	Radiological exposure – total estimated worker dose per Energy Generated (as leading indicator for public dose potential
EG01	Bin B	Bin B	Bin B	Bin B
EG02	Bin C	Bin B	Bin B	Bin B
EG03	Bin C	Bin B	Bin C	Bin B
EG04	Bin A	Bin B	Bin A	Bin B
EG05	Bin C	Bin B	Bin B	Bin B
EG06	Bin B	Bin C	Bin B	Bin B
EG07	Bin B	Bin C	Bin B	Bin B
EG08	Bin B	Bin C	Bin A	Bin B
EG09	Bin A	Bin B	Bin A	Bin B
EG10	Bin A	Bin B	Bin C	Bin B
EG11	Bin B	Bin B	Bin B	Bin B
EG12	Bin B	Bin B	Bin C	Bin B
EG13	Bin B	Bin B	Bin B	Bin B
EG14	Bin A	Bin B	Bin A	Bin B
EG15	Bin B	Bin B	Bin B	Bin B
EG16	Bin B	Bin B	Bin B	Bin B
EG17	Bin B	Bin B	Bin B	Bin B
EG18	Bin B	Bin B	Bin B	Bin B
EG19	Bin B	Bin B	Bin D	Bin B

EG20	Bin B	Bin B	Bin D	Bin B
EG21	Bin B	Bin B	Bin B	Bin B
EG22	Bin B	Bin B	Bin B	Bin B
EG23	Bin A	Bin B	Bin A	Bin B
EG24	Bin A	Bin B	Bin A	Bin B
EG25	Bin B	Bin B	Bin B	Bin B
EG26	Bin A	Bin B	Bin C	Bin B
EG27	Bin B	Bin B	Bin C	Bin B
EG28	Bin A	Bin B	Bin B	Bin B
EG29	Bin A	Bin B	Bin B	Bin B
EG30	Bin A	Bin B	Bin A	Bin B
EG31	Bin B	Bin B	Bin B	Bin B
EG32	Bin B	Bin B	Bin B	Bin B
EG33	Bin A	Bin B	Bin B	Bin B
EG34	Bin A	Bin B	Bin B	Bin B
EG35	Bin B	Bin B	Bin B	Bin B
EG36	Bin B	Bin B	Bin B	Bin B
EG37	Bin A	Bin B	Bin B	Bin B
EG38	Bin A	Bin B	Bin C	Bin B
EG39	Bin B	Bin B	Bin B	Bin B
EG40	Bin A	Bin B	Bin A	Bin B

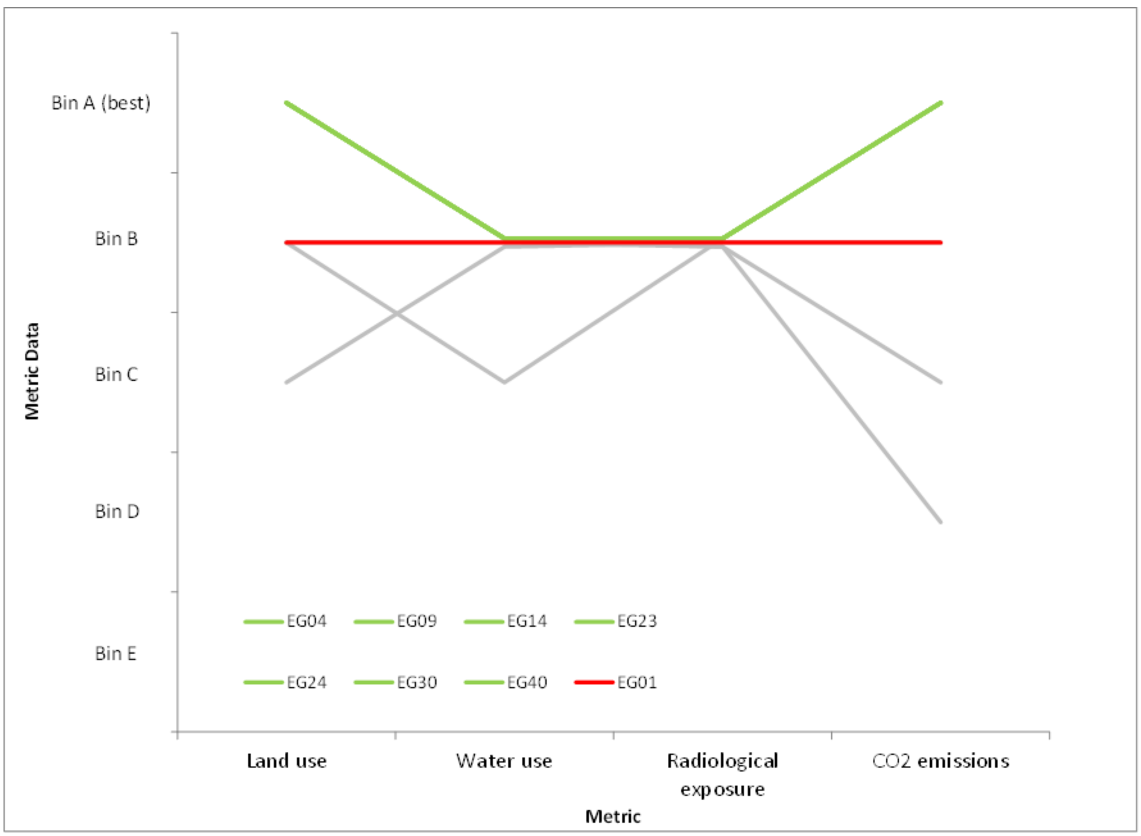

Figure E-5.1. Metric data for 40 Evaluation Groups on the Four Environmental Impact Metrics.

E-5.1. Shape Functions and Metric Tradeoff Factors for Environmental Impact

Shape functions represent the relative importance of changes or differences in the metric data for a single metric, and metric tradeoff factors reflect the relative importance of changes in one metric versus changes in the others. Different perspectives on the importance of these changes are possible. This evaluation and screening deliberately considers a range of possible perspectives in the criterion-level evaluations (as well as in the evaluations to be presented in Appendix F that consider multiple criteria). The goals of considering these multiple perspectives are two-fold: first is to identify any Evaluation Groups that perform well and might be considered promising under a variety of different perspective, and second is to identify any Evaluation Group that might perform well under only one or a few perspectives. The first group might be considered the "robust" high performers, while the second group highlights Evaluation Groups that might best meet a particular point of view.

The shape functions defined for the four Evaluation Metrics for Environmental Impact are described in Table E-5.2 and illustrated in Figures E-5.2 to E-5.5. From the shape functions, utility values can be assigned to each of the bins for each metric. For all metrics, the shape functions are linear in terms of the underlying quantity being considered (e.g., reducing land/water/CO_2/dose by one unit gives the same valuation improvement whether the starting point is high or low). Because the bin definitions themselves are not linear, the graphical representations in Figures E-5.2 to E-5.5 appear non-linear – they are simply "counteracting" the non-linear nature of the bin structure.

Table E-5.2. Shape Functions Environmental Impact Metrics.

Land Use per Energy Generated: One perspective evaluated
Shape Function is linear in terms of land use per energy generated, reflecting a perspective that every unit reduction in land use is equally important for operational issues.
Water Use per Energy Generated: One perspective evaluated
Shape Function 1 is linear in terms of water use per energy generated, reflecting a perspective that every unit reduction in water use is equally important for operational issues.
Carbon Emission – CO_2 released per Energy Generated: One perspective evaluated
Shape Function 1 is linear in terms of CO_2 released water use per energy generated, reflecting a perspective that every unit reduction in CO_2 release use is equally important for operational issues.
Radiological exposure – total estimated worker dose per Energy Generated (as leading indicator for public dose potential: Two perspectives were evaluated
Shape Function 1 is linear in terms of radiological exposure to the worker. This shape function treats bin "A" as equal to 0.5 person-Sv/GWe-yr , bin "B" as the midpoint and bin "C" as equal to 5 person-Sv/GWe-yr.

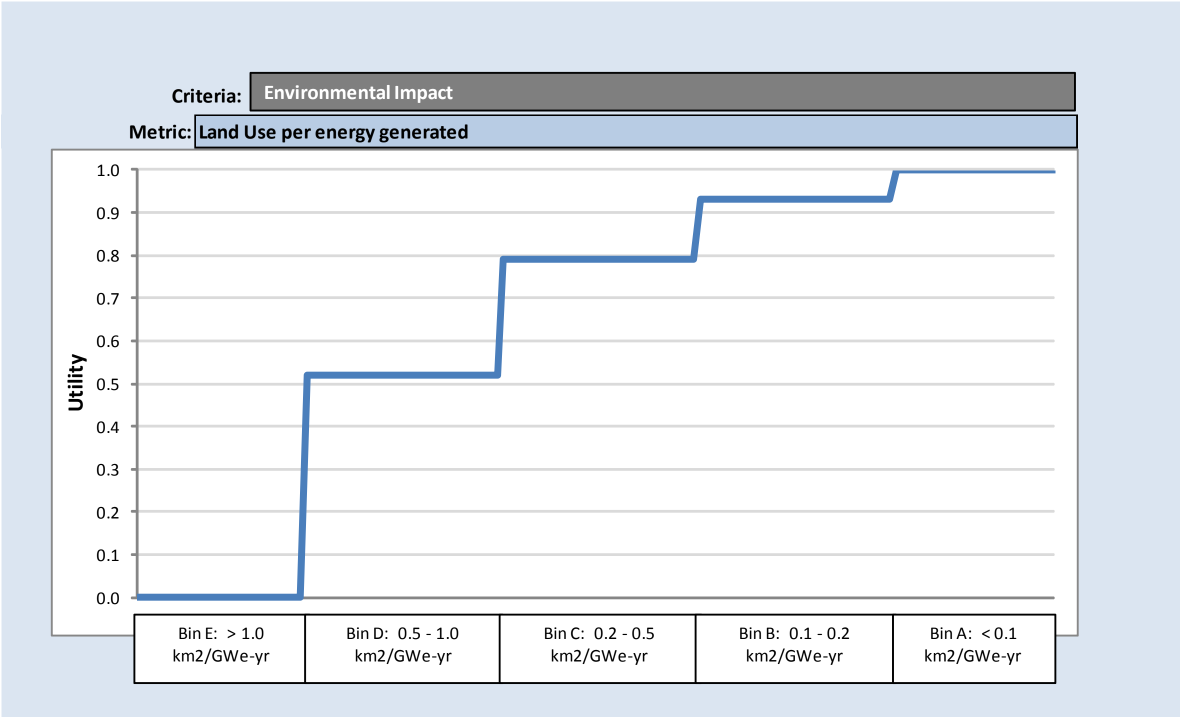

Figure E-5.2. Shape Function 1 for Land Use per Energy Generated.

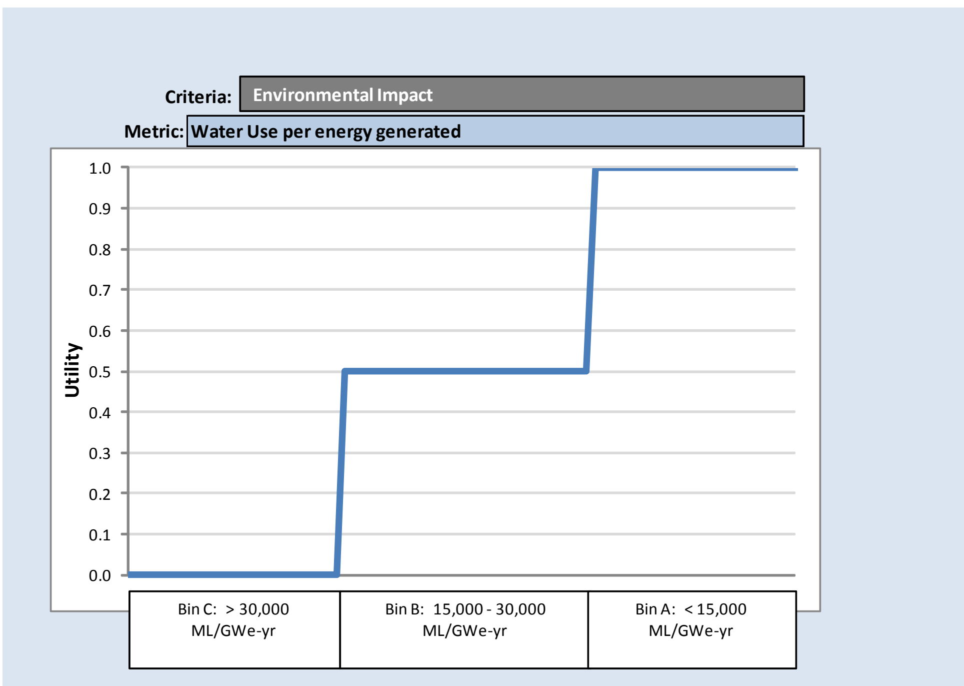

Figure E-5.3. Shape Function 1 for Water Use per Energy Generated.

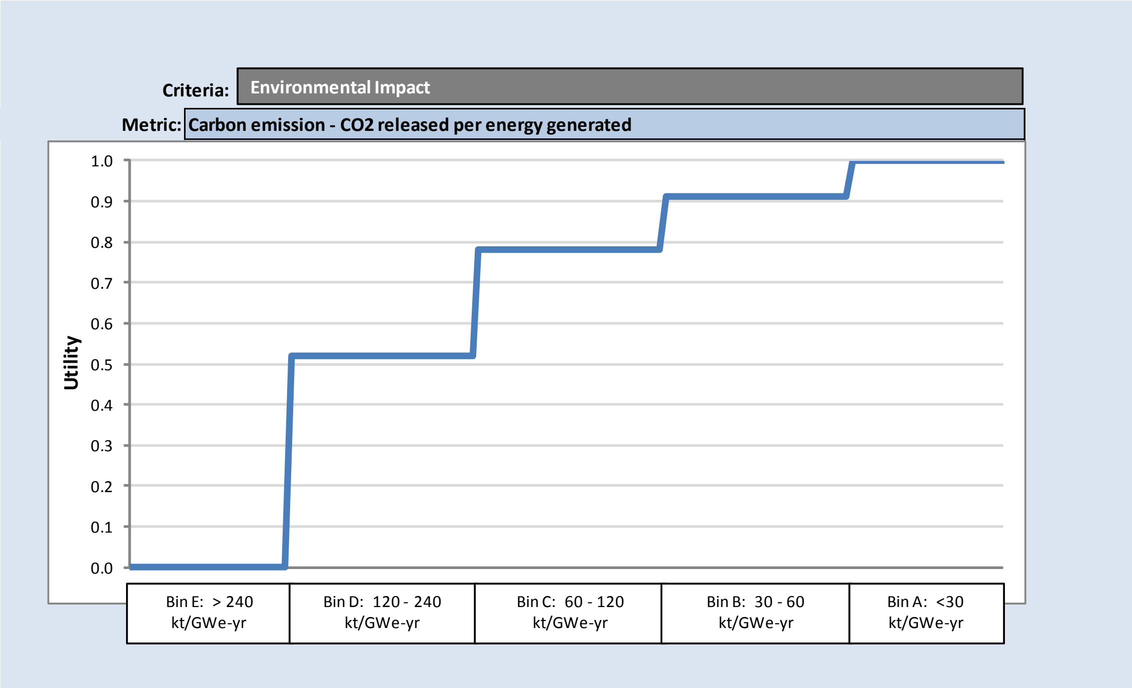

Figure E-5.4. Shape Function 1 for Carbon Emission – CO_2 released per Energy Generated.

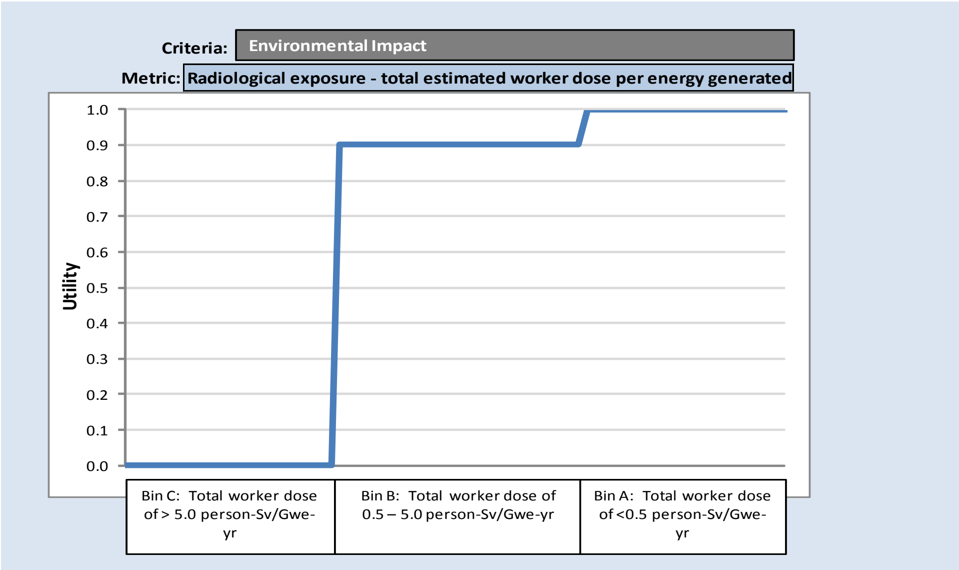

Figure E-5.5. Shape Function 1 for Radiological Exposure – Total Estimated Worker Dose per Energy Generated (as Leading Indicator for Public Dose Potential).

For the purpose of informing on the Environmental Impact criterion, various viewpoints have been examined. Four sets of metric tradeoff factors were defined to explore different perspectives on the relative importance of differences between metrics, as shown in Table E-5.3, and reflect the following considerations:

Set 1: Emphasizes changes in Radiological exposure – total estimated worker dose per Energy Generated (as leading indicator for public dose potential) and Water Use per Energy Generated.

Set 2: Focuses only on changes in Radiological exposure – total estimated worker dose per Energy Generated (as leading indicator for public dose potential) and Carbon Emission – CO_2 released per Energy Generated.

Set 3: Emphasizes differences in Water Use per Energy Generated.

Set 4: Places equal emphasis on changes for each of the four metrics.

Table E-5.3. Metric Tradeoff Factors for Environmental Impact Metrics.

	Metric tradeoff factors representing the relative importance of changes in each metric, considering the entire range defined by the bins for each metric			
Metric	**Set 1**	**Set 2**	**Set 3**	**Set 4**
Land Use per Energy Generated	0.20	0.00	0.20	0.25
Water Use per Energy Generated	0.30	0.00	0.40	0.25
Carbon Emission – CO_2 released per Energy Generated	0.15	0.50	0.20	0.25
Radiological exposure – total estimated worker dose per Energy Generated (as leading indicator for public dose potential	0.35	0.50	0.20	0.25

E-5.2 Results for the Environmental Impact Criterion

With only one shape function per Environmental Impact Criterion metric there are only 4 unique combinations of shape functions and metric tradeoff factors considered in evaluating and ranking Evaluation Groups within this criterion.

The resulting data for the 4 combinations are shown in Figure E-5.6, and Table E-5.4. The figure shows the calculated utility value on the Environmental Impact Criterion considering all four metrics, using the shape functions and metric tradeoff factors specified; the table shows the same values, with the Evaluation Groups sorted by utility value for each set of shape functions and metric tradeoff factors. The utility scale ranges from 0 to 1, across the range of bins for all four criteria: an Evaluation Group would have to be in the best performing bin on all four metrics to have an Environmental Impact Criterion utility value of 1, and would have to be in the worst performing bin on all four metrics to have a utility value of 0. Neither of these cases exists.

Exploratory analyses were conducted to reduce this set (if possible) to a smaller set that would still capture any significant differences between ranking and evaluation results.

Several results are apparent:

- For trade-off factor sets 1, 3 and 4 the ordered ranking of the Evaluation Groups is the same.
- The best performing Evaluation Groups based on the metric data in Table E-5.1 have the highest environmental impact utility using any of the four Environmental Impact Criterion trade-off factors, meaning they perform as well or better than any other Evaluation Groups on all four metrics, as listed at the start of this section.

- Using trade-off factor set 2 (emphasizing the importance of Carbon Emission – CO_2 released per Energy Generated and Radiological exposure – total estimated worker dose per Energy Generated, as leading indicator for public dose potential), one additional Evaluation Group (EG08) receives the same environmental impact utility as the seven Evaluation Groups previously identified. Since in this trade-off factor set land use and water use are not considered and all Evaluation Groups fall into the same bin for Radiological Exposure, this trade-off factor set collapses to ordering based only on the Carbon Emissions metrics and the eight Evaluation Groups contained in Bin "A" for the Carbon Emissions metric come out on top.

- The Basis of Comparison, EG01, is never in the top set of Evaluation Groups, but is generally near the top: there are more Evaluation Groups that perform worse than EG01 in terms of their environmental impact than perform better.

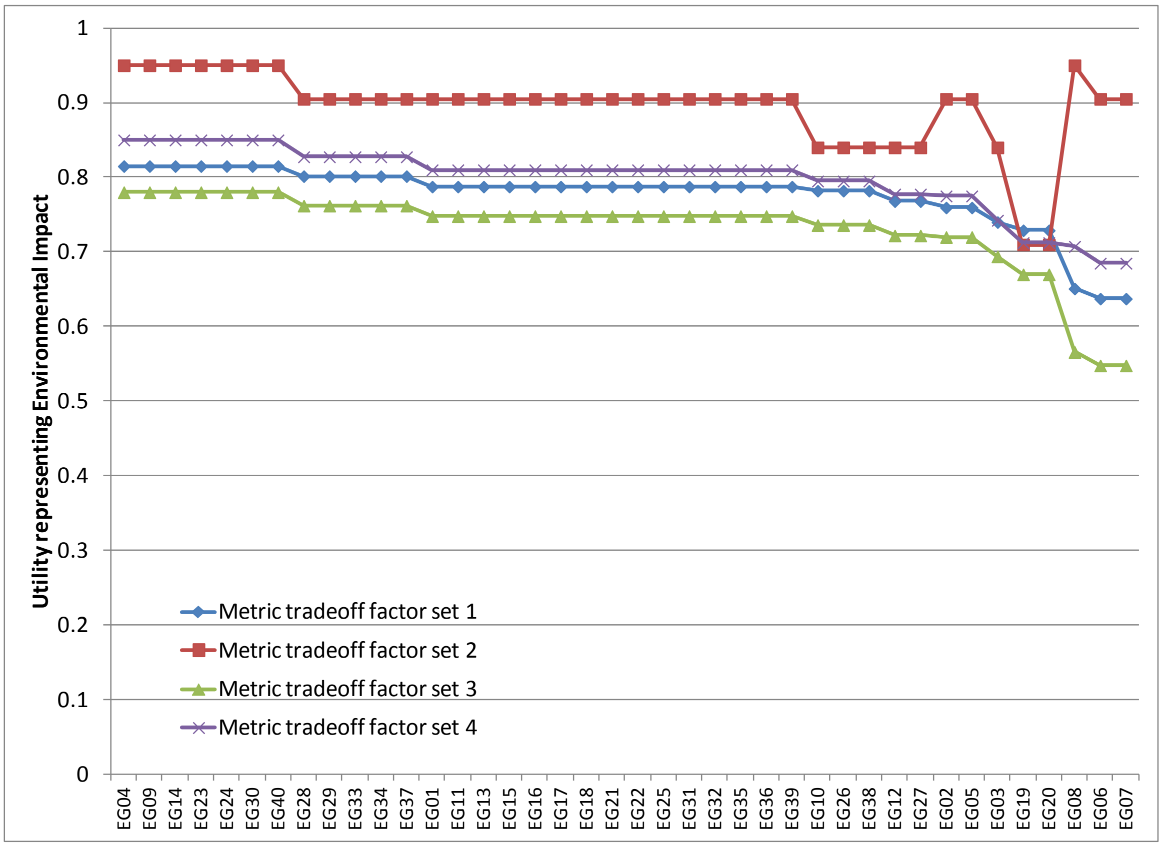

Figure E-5.6. Environmental Impact Criterion Results for Each Evaluation Group, using the Four Trade-off Factors.

Table E-5.4. Ranking of Evaluation Groups by Calculated Utility for the Environmental Impact Criterion with Each of the Four Trade-off Factor Sets.

Trade-off Set 1		Trade-off Set 2		Trade-off Set 3		Trade-off Set 4	
EG	Utility TF1	EG	Utility TF2	EG	Utility TF3	EG	Utility TF4
EG04	0.815	EG04	0.950	EG04	0.780	EG04	0.850
EG09	0.815	EG08	0.950	EG09	0.780	EG09	0.850
EG14	0.815	EG09	0.950	EG14	0.780	EG14	0.850
EG23	0.815	EG14	0.950	EG23	0.780	EG23	0.850
EG24	0.815	EG23	0.950	EG24	0.780	EG24	0.850
EG30	0.815	EG24	0.950	EG30	0.780	EG30	0.850
EG40	0.815	EG30	0.950	EG40	0.780	EG40	0.850
EG28	0.802	EG40	0.950	EG28	0.762	EG28	0.828
EG29	0.802	EG01	0.905	EG29	0.762	EG29	0.828
EG33	0.802	EG02	0.905	EG33	0.762	EG33	0.828
EG34	0.802	EG05	0.905	EG34	0.762	EG34	0.828
EG37	0.802	EG06	0.905	EG37	0.762	EG37	0.828
EG01	0.788	EG07	0.905	EG01	0.748	EG01	0.810
EG11	0.788	EG11	0.905	EG11	0.748	EG11	0.810
EG13	0.788	EG13	0.905	EG13	0.748	EG13	0.810
EG15	0.788	EG15	0.905	EG15	0.748	EG15	0.810
EG16	0.788	EG16	0.905	EG16	0.748	EG16	0.810
EG17	0.788	EG17	0.905	EG17	0.748	EG17	0.810
EG18	0.788	EG18	0.905	EG18	0.748	EG18	0.810
EG21	0.788	EG21	0.905	EG21	0.748	EG21	0.810
EG22	0.788	EG22	0.905	EG22	0.748	EG22	0.810
EG25	0.788	EG25	0.905	EG25	0.748	EG25	0.810
EG31	0.788	EG28	0.905	EG31	0.748	EG31	0.810
EG32	0.788	EG29	0.905	EG32	0.748	EG32	0.810
EG35	0.788	EG31	0.905	EG35	0.748	EG35	0.810
EG36	0.788	EG32	0.905	EG36	0.748	EG36	0.810
EG39	0.788	EG33	0.905	EG39	0.748	EG39	0.810
EG10	0.782	EG34	0.905	EG10	0.736	EG10	0.795
EG26	0.782	EG35	0.905	EG26	0.736	EG26	0.795
EG38	0.782	EG36	0.905	EG38	0.736	EG38	0.795
EG12	0.768	EG37	0.905	EG12	0.722	EG12	0.778
EG27	0.768	EG39	0.905	EG27	0.722	EG27	0.778
EG02	0.760	EG03	0.840	EG02	0.720	EG02	0.775
EG05	0.760	EG10	0.840	EG05	0.720	EG05	0.775
EG03	0.740	EG12	0.840	EG03	0.694	EG03	0.743
EG19	0.729	EG26	0.840	EG19	0.670	EG19	0.713
EG20	0.729	EG27	0.840	EG20	0.670	EG20	0.713
EG08	0.651	EG38	0.840	EG08	0.566	EG08	0.708
EG06	0.638	EG19	0.710	EG06	0.548	EG06	0.685
EG07	0.638	EG20	0.710	EG07	0.548	EG07	0.685

E-5.3. Initial Criterion-level Analysis

In calculating and presenting criterion-level analyses, it is convenient to choose an initial perspective, i.e., one metric tradeoff factor set, to illustrate the types of analyses that were conducted and to describe a set of results. For the Environmental Impact Criterion, the initial analyses are conducted using metric tradeoff factor set 4, which places equal emphasis on each of the 4 associated metrics. Note that the results shown in Figure E-5.6 are sorted by these values.

Similar to the discussion of promising groups with respect to each individual metric in Appendix D, 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.

There are 4 metrics for Environmental Impact and examination of the data at the metric level reveals:

- Land use – improvement is possible (from the 0.1-0.2 km^2 / GWe-yr bin down to the < 0.1 km^2 / GWe-yr bin, the best bin)
- Water use – improvement is not possible at the fuel cycle level. Any improvements would come at the implementing technology level and would be applicable to any fuel cycle
- CO_2 – improvement is possible (from the 30,000-60,000 t / GWe-yr bin down to the < 30,000 t / GWe-yr bin, the best bin)
- Radiation – improvement is not possible at the fuel cycle level. Any improvements would come from changes at the facility design level, and would be applicable to any fuel cycle.

Identifying thresholds. Threshold utility values were identified based on direct consideration of the metric data, using the calculated values based on shape functions and metric tradeoff factors described above. In addition to the highest achieved benefit utility, two potential threshold values were defined. Those values and the logic by which they were identified are shown in Table E-5.5 and summarized below:

- The highest achieved benefit utility was defined based on the highest bins that were obtained for any Evaluation Group.
- Threshold 1 was defined by decreasing the threshold for "benefit" from that of the best performing Evaluation Groups to include Evaluation Groups that have the same level of performance on CO_2 Emissions as the Basis of Comparison (which is one bin "worse" that the best performing groups)
- A second threshold was also examined. This was defined by decreasing the threshold for "promise" from that of the best performing Evaluation Groups to include Evaluation Groups that have the same level of performance on the Land Use as the Basis of Comparison (which is one bin "worse") than that of the best performing groups.

Table E-5.5. Thresholds Considered for Identifying Promising Groups with Respect to the Environmental Impact Criterion.

Threshold Type	Land Use per Energy Generated	Water Use per Energy Generated	Carbon Emission – CO_2 Released per Energy Generated	Radiological exposure – total estimated worker dose per Energy Generated (as leading indicator for public dose potential	Utility representing Environmental Impact
Highest achieved benefit utility (Utility = 0.850)	Bin A: < 0.1 km^2/GWe-yr	Bin B: ≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr	Bin A: < 30 kt CO_2/GWe-yr	Bin B: ≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr	0.850
Threshold 1 (Utility = 0.828)	Bin A: < 0.1 km^2/GWe-yr r	Bin B: ≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr r	Bin B: ≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr	Bin B: ≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr	0.828
Additional threshold considered (Utility = 0.833)	Bin B: ≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr	Bin B: ≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr	Bin A: < 30 kt CO_2/GWe-yr r	Bin B: ≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr	0.833
EG01	Bin B: ≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr	Bin B: ≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr	Bin B: ≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr	Bin B: ≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr	0.810

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 has been relaxed in going from one threshold to the next threshold.

The second potential threshold utility value falls between the utility values of the highest achieved benefit utility and Threshold 1 but added no insight and was dropped from further analysis. What was observed using the highest achieved utility and Threshold 1 is that:

- The highest achieved benefit utility identifies EG04, EG09, EG14, EG23, EG24, EG30 and EG40 as promising groups, as discussed above.
- Threshold 1 adds EG28, EG29, EG33, EG34, and EG37 to the seven Evaluation Groups identified above.
  - 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
  - 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
  - EG37 - Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in both fast and thermal critical reactors.
- The next cluster of 15 fuel cycle Evaluation Groups had a criterion utility value of 0.810 and contained the Basis of Comparison, indicating comparable performance on this criterion to the Basis of Comparison.

The Evaluation Groups that are identified as promising using threshold values and metric trade-off factor set 4 (equal) weighting are shown in Table E-5.6:

Table E-5.6. Environmental Impact Criterion Results Based on Thresholds.

Threshold Type	Evaluation Groups At or Above Threshold
Highest Achieved Benefit Utility	EG04, EG09, EG14, EG23, EG24, EG30, EG40
Threshold 1	EG04, EG09, EG14, EG23, EG24, EG28, EG29, EG30, EG33, EG34, EG37, EG40

Examination of the sets of promising options:

- Seven Evaluation Groups are highly ranked (they are in the top 10) under all perspectives. These are the robust high performing groups described above.
- These all contain fast reactors without enrichment. They span once through, limited recycle and continuous recycle and contain both uranium and thorium systems.
- These all have high resource utilization which impacts land usage primarily in the FEFC and in disposal.
- All of the Evaluation groups added by the use of Threshold 1 are continuous recycle. All contain fast reactors and all but one is without enrichment.

E-5.4 Environmental Impact and Development Challenge

In addition to the ordering based solely on benefit (the calculated utility value for the Environmental Impact Criterion) it may be useful to consider both the benefit and the challenges associated with fuel cycle development and deployment when considering the overall promise of a fuel cycle option.

This has been done by ranking Evaluation Groups within each of the promising sets identified above by the ratio of incremental promise to in incremental challenge. Figure E-5.7 plots the benefit and challenge of each Evaluation Group, with the utility representing benefit calculated as the Environmental Impact utility using trade-off factor set 4. Table E-5.7 shows the ranked lists of Evaluation Groups for each threshold based on the ratio of incremental benefit to incremental challenge.

Because the seven Evaluation Groups in the “highest utility” group all have the same benefit utility, the ranking in Table E-5.9 simply orders those groups from least to greatest challenge.

The five additional Evaluation Groups that meet Threshold 1 all have the same benefit utility as each other, EG28, EG29, EG33, EG34, and E37, and the least challenging of that set has a slightly lower ratio than the most challenging Evaluation Group in the highest utility group (EG40).

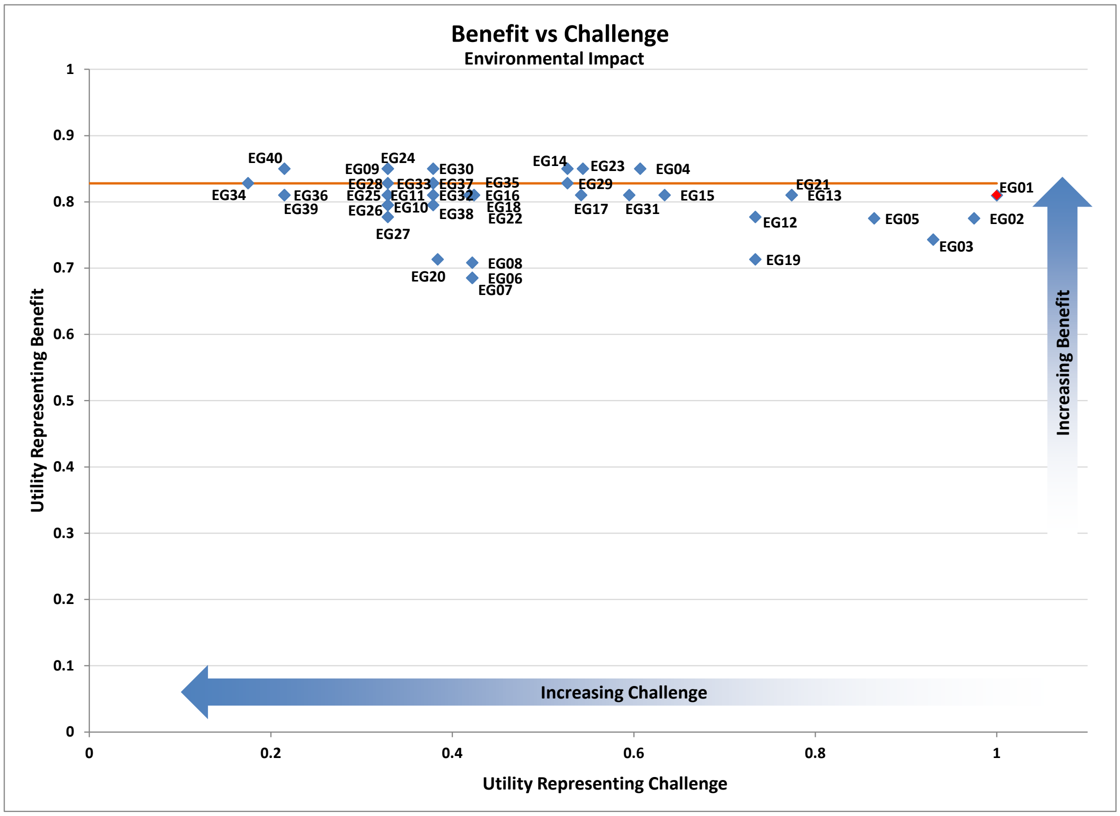

Figure E-5.7. Environmental Impact Criterion versus Challenge Represented by Development and Deployment Risk.

Table E-5.7. Environmental Impact Criterion Results Based on Consideration for Benefit-to-Challenge Ratio.

Highest Achieved Utility Ordering (Utility = 0.850)		Threshold 1 Ordering (Utility = 0.828)	
Evaluation Group	Ratio	Evaluation Group	Ratio
EG04	0.102	EG04	0.102
EG23	0.088	EG23	0.088
EG14	0.085	EG14	0.085
EG30	0.064	EG30	0.064
EG09	0.060	EG09	0.060
EG24	0.060	EG24	0.060
EG40	0.051	EG40	0.051
		EG29	0.038
		EG33	0.029
		EG37	0.029
		EG28	0.027
		EG34	0.022

Summary: Characteristics of Promising Groups

From a variety of perspectives and definition of "promise," the promising groups when only considering the environmental impact criterion tend to contain fast reactors without enrichment. They span once through, limited recycle and continuous recycle and contain both uranium and thorium systems.

– The seven best-performing Evaluation Groups are EG04, EG09, EG14, EG23, EG24, EG30, and EG40

– Additional groups that might be considered promising include EG28, EG29, EG33, EG34, and EG37

Supporting R&D and Insights

Based on the identified Evaluation Groups above, arising from the conditional statements on promising options, the following are the R&D activities that would enable the deployment and better performance of the Evaluation Groups:

- Separation technologies for the limited and continuous recycle options
- Extremely high burnup fuels (>30%) required for options with no enrichment and no fuel separations
  - Primarily, advanced cladding materials that can withstand high irradiation levels at reactor temperatures
  - Fuel that can retain or safely release fission products from high burnup fuels
- Recycle fuels
- Advanced reactors
  - Fast-spectrum reactor
  - Breed and burn reactor concepts that utilize high burnup fuels
- Critical thermal or fast spectrum reactors and EDSs with thermal or fast spectrum subcritical blankets, using fuel(s) of natural thorium
  - Fast-spectrum ADSs

Thorium mining, milling, and fuel processing and preparation technologies to implement options using thorium.

E-6. Resource Utilization

Review of Metric Data for Resource Utilization Criterion

Two Evaluation Metrics were identified as informing on the Resource Utilization Criterion. These are the *Natural Uranium Required* and *Natural Thorium Required* metrics. Moving from the metric level comparison (described in Appendix D) to a criterion level comparison requires that the performance of an Evaluation Group relative to the performance of the Basis of Comparison on the two metrics be considered simultaneously. Table E-6.1 shows the metric data for all 40 Evaluation Groups on both metrics. Fourteen Evaluation Groups can be identified as "dominant" in terms of the Resource Utilization criterion, as they all have the best possible metric data (Bin A) for both of the Evaluation Metrics:

- EG06 - Once-through using Th fuel to very high burnup in thermal 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
- EG09 - Limited recycle of U/TRU with new natural-U fuel to very high burnup in fast 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
- EG26 - Continuous recycle of ^{233}U/Th with new Th fuel in thermal 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
- 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
- EG38 - Continuous recycle of ^{233}U/Th with new Th fuel in both fast and thermal critical reactors
- EG40 - Continuous recycle of ^{233}U/Th with new Th fuel in fast EDS and thermal critical reactors

The metric data for these Evaluation Groups are represented by the green rows in Table E-6.1; the metric data for the Basis of Comparison (EG01) is represented by the light red row. The uncolored rows represent the metric data for other Evaluation Groups. Any ranking or comparison of these (non-dominant) groups is a matter of perspective: whether one Evaluation Group is "better" than another with respect to Resource Utilization criterion depends on the relative importance one attaches to the differences between bins for each metric, and on the relative importance of differences across the metrics. As described in Appendix A, these perspectives are represented in the Evaluation and Screening by *shape functions* and *metric tradeoff factors*. The fourteen dominant Evaluation Groups will always rank at the top of any comparative list for this criterion, regardless of the perspectives, because they outperform the other groups based on the metric data directly.

Table E-6.1. Resource Utilization Metric Bin Data.

Evaluation Group	Natural Uranium Required	Natural Thorium Required
EG01	Bin D	Bin A
EG02	Bin D	Bin A
EG03	Bin D	Bin A
EG04	Bin B	Bin A
EG05	Bin D	Bin B
EG06	Bin A	Bin A
EG07	Bin A	Bin A
EG08	Bin A	Bin A
EG09	Bin A	Bin A

Evaluation Group	Natural Uranium Required	Natural Thorium Required
EG10	Bin A	Bin B
EG11	Bin C	Bin A
EG12	Bin C	Bin A
EG13	Bin D	Bin A
EG14	Bin B	Bin A
EG15	Bin D	Bin A
EG16	Bin D	Bin A
EG17	Bin D	Bin A
EG18	Bin D	Bin A
EG19	Bin C	Bin A
EG20	Bin C	Bin A
EG21	Bin D	Bin A
EG22	Bin D	Bin A
EG23	Bin A	Bin A
EG24	Bin A	Bin A
EG25	Bin C	Bin A
EG26	Bin A	Bin A
EG27	Bin D	Bin A
EG28	Bin A	Bin A
EG29	Bin A	Bin A
EG30	Bin A	Bin A
EG31	Bin C	Bin A
EG32	Bin C	Bin A
EG33	Bin A	Bin A
EG34	Bin A	Bin A
EG35	Bin D	Bin A
EG36	Bin D	Bin A
EG37	Bin B	Bin A
EG38	Bin A	Bin A
EG39	Bin C	Bin A
EG40	Bin A	Bin A

Note: The Metric Bin descriptions and data ranges for the Resource Utilization Metrics are given in Appendix C. Metrics are normalized to per energy generated.

E-6.1 Shape Functions and Metric Tradeoff Factors for Resource Utilization

Shape functions represent the relative importance of changes or differences in the metric data for a single metric, and metric tradeoff factors to reflect the relative importance of changes in one metric versus changes in the others. Different perspectives on the importance of these changes are possible. This evaluation and screening deliberately considers a range of possible perspectives in the criterion-level evaluations (as well as in the evaluations to be presented in Appendix F that consider multiple criteria). The goals of considering these multiple perspectives are two-fold: first is to identify any Evaluation Groups that perform well and might be considered promising under a variety of different perspective, and second is to identify and be able to call out any Evaluation Group that might perform well under only one or a few perspectives. The first group might be considered the "robust" high performers, while the second group highlights Evaluation Groups that might best meet a particular set of interests or needs.

The shape functions defined for the two Evaluation Metrics for Resource Utilization are described in Table E-6.2 and are illustrated in Figures E-6.1 and E-6.2.

Table E-6.2. Shape Functions for Resource Utilization Metrics.

Shape Functions for Natural Uranium Required per Energy Generated
Shape Function 1 is logarithmic in mass, reflecting the perspective that an order of magnitude change in natural uranium required is important, consistent with a view to conserve resources.
Shape Function 2 is linear in mass, reflecting the perspective that every unit change in natural uranium required is equally important, consistent with a view that there are sufficient resources for use in nuclear systems.
Shape Functions for Natural Thorium Required per Energy Generated
Shape Function 1 is logarithmic in mass, reflecting the perspective that an order of magnitude change in natural thorium required is important, consistent with a view to conserve resources.
Shape Function 2 is linear in mass, reflecting the perspective that every unit change in natural thorium required is equally important, consistent with a view that there are sufficient resources for use in nuclear systems.

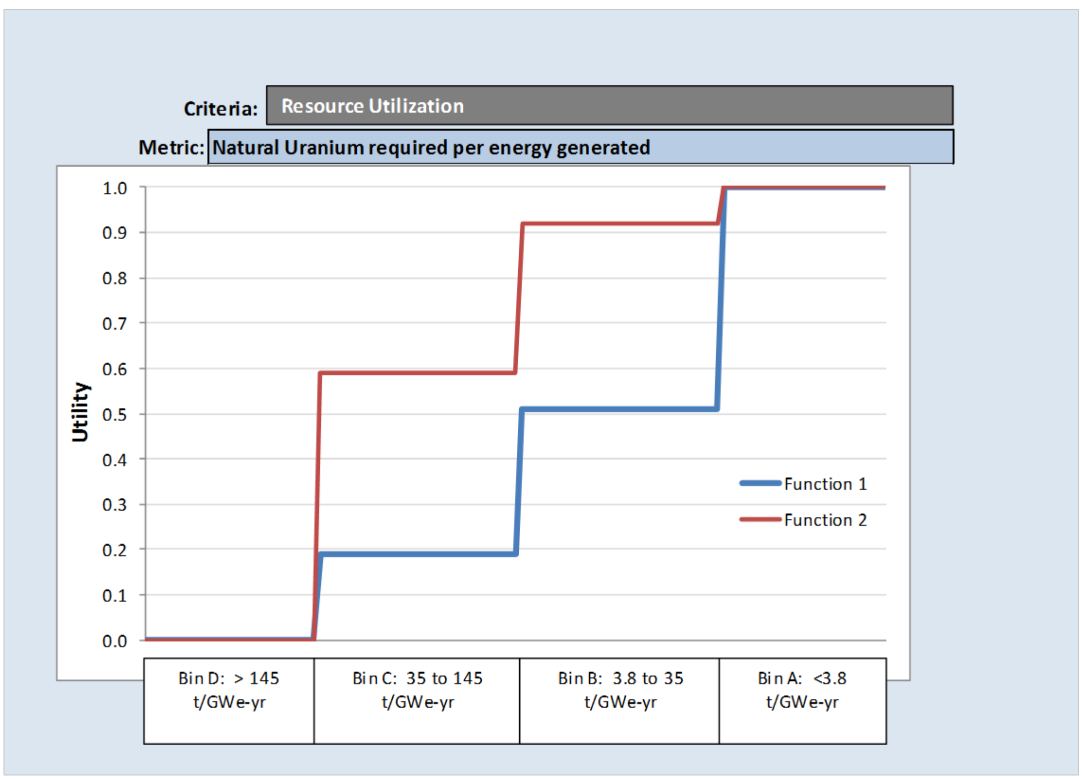

Figure E-6.1. Shape Functions 1 and 2 for Natural Uranium Required per Energy Generated.

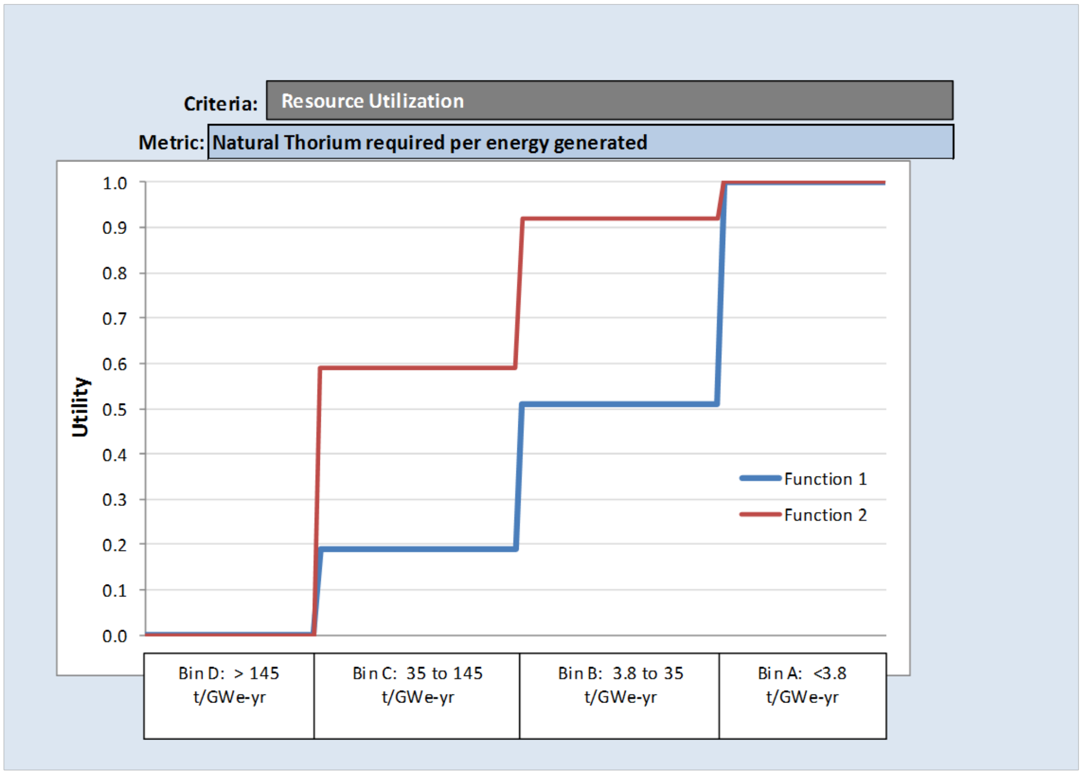

Figure E-6.2. Shape Functions 1 and 2 for Natural Thorium Required per Energy Generated.

Two sets of metric tradeoff factors were defined to explore different perspectives on the relative importance of differences between metrics. Table E-6.3 summarizes the metric tradeoff factor sets, which reflect the following considerations:

Set 1: Uranium and Thorium resources are of equal value, so changes in the amount of each resource needed are considered of comparable benefit.

Set 2: Uranium resource is scarcer than that of thorium and its utilization needs more careful management: thus changes in uranium required has a higher tradeoff factor than changes in thorium required, indicating there is more value to reducing the amount of uranium required than to reducing thorium requirements by the same amount (and more cost to increasing uranium requirements than to increasing thorium requirements). The ratio of the tradeoff values is consistent with the presumed ratio of 4:1 abundance of thorium relative to uranium in nature.

Table E-6.3. Tradeoff Factors for Resource Utilization Metrics.

	Metric tradeoff factors representing the relative importance of changes in each metric, considering the entire range defined by the bins for each metric	
Metric Type	**Set 1**	**Set 2**
Natural Uranium required per energy generated	0.50	0.80
Natural Thorium required per energy generated	0.50	0.20

In calculating and presenting criterion-level and scenario-level (see Appendix F-2) analyses, it is convenient to choose an initial perspective (one set of shape functions and one metric tradeoff factor set) to illustrate the types of analyses that were conducted and to describe a set of results, followed by an exploration of whether and how those results change under different shape functions and metric tradeoff factors. For the Resource utilization Criterion, those analyses were conducted using Shape Function 1 for all Evaluation Metrics, and using metric Tradeoff Factor set 2, which emphasizes the perspective that uranium resource is scarcer than that of thorium and uranium utilization needs to be managed.

Insights on Promising Options for the Resource Utilization Criterion

The results obtained with the initial set of shape functions and tradeoff factors are discussed in this section. Those on the sensitivity analyses considering 4 different combinations of shape functions and tradeoff factors are provided in Section E-6.2.

Similar to the discussion of promising groups with respect to each individual metric in Appendix D, 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.

Benefit and challenge results are shown in Figure E-6.3.

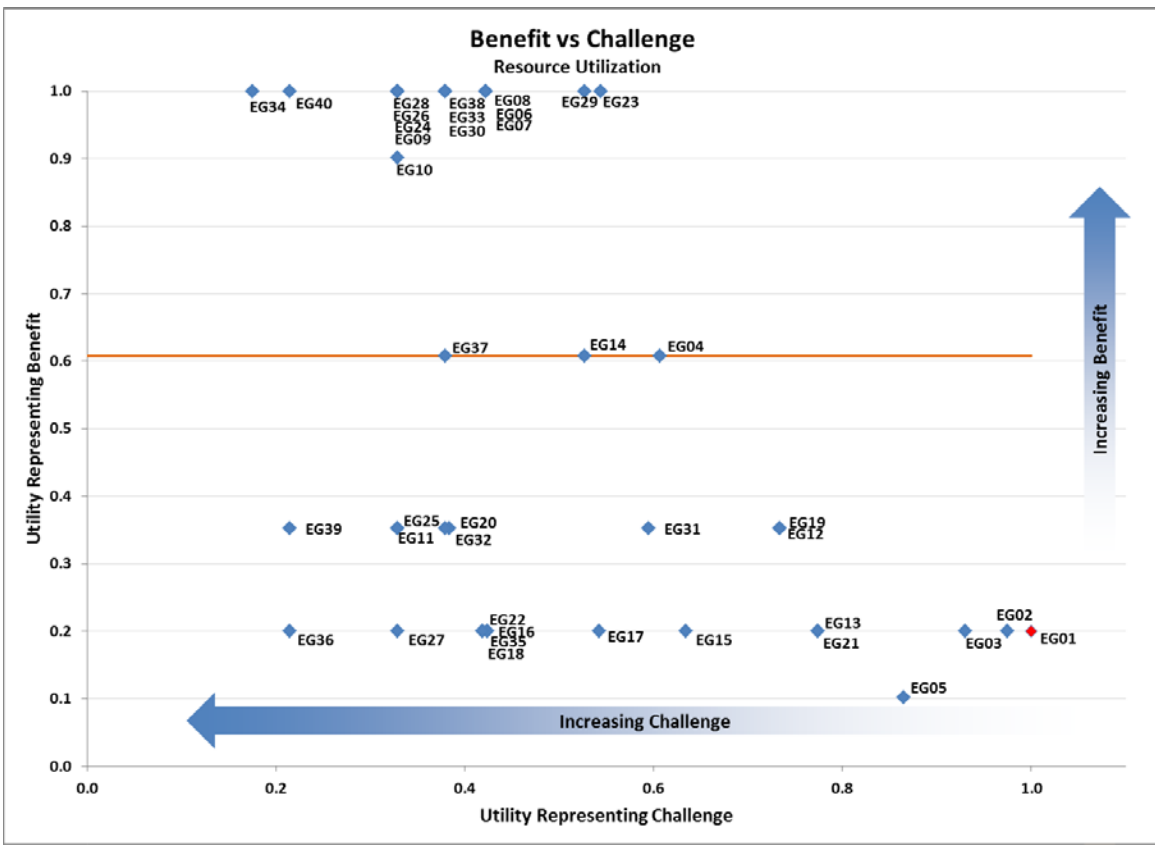

Figure E-6.3. Resource Utilization Utility versus Challenge Represented by Development and Deployment Risk Utility.

Two thresholds were defined for identifying potentially promising sets of Evaluation Groups with respect to the Resource Utilization criterion. The thresholds were defined by considering the specific improvements for each Evaluation Metric that were considered as potentially significant in Appendix D, and combining them using the initial shape functions and metric tradeoff factors to yield a utility. Table E-6.4 shows the thresholds and Table E-6.5 shows the Evaluation Groups that meet each of the thresholds. Rationales for the threshold values and a discussion of the results follow the table.

Table E-6.4. Thresholds Considered for Identifying Promising Groups with Respect to the Resource Utilization Criterion.

Threshold Type	Natural Uranium Required	Natural Thorium Required	Utility representing Resource Utilization
Highest achieved benefit utility (Utility=1)	Bin A: < 3.8 t/GWe-yr	Bin A: < 3.8 t/GWe-yr	1.000
Threshold 1 (Utility=0.608)	Bin B: 3.8 to < 35.0 t/GWe-yr	Bin A: < 3.8 t/GWe-yr	0.608
EG01	Bin D: ≥ 145.0 t/GWe-yr	Bin A: < 3.8 t/GWe-yr	0.200

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 has been relaxed in going from one threshold to the next threshold.

Table E-6.5. Resource Utilization Criterion Results Based on Thresholds.

Threshold Type	Evaluation Groups Within Threshold
Highest Achieved Benefit Utility (Utility = 1.000)	EG06, EG07, EG08, EG09, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG38, EG40
Threshold 1 (Utility = 0.608)	EG04, EG06, EG07, EG08, EG09, EG10, EG14, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG37, EG38, EG40

Table E-6.6. Resource Utilization Criterion Results Based on Consideration for Benefit-to-Challenge Ratio.

Highest Achieved Utility Ordering (Utility = 1.00)		Threshold 1 Ordering (Utility = 0.608)	
Evaluation Group	Ratio	Evaluation Group	Ratio
EG23	1.754	EG23	1.754
EG29	1.691	EG29	1.691
EG06	1.384	EG06	1.384
EG07	1.384	EG07	1.384
EG08	1.384	EG08	1.384
EG30	1.288	EG30	1.288
EG33	1.288	EG33	1.288
EG38	1.288	EG38	1.288
EG09	1.192	EG09	1.192
EG24	1.192	EG24	1.192
EG26	1.192	EG26	1.192
EG28	1.192	EG28	1.192

EG40	1.019	EG10	1.046
EG34	0.970	EG04	1.038
		EG40	1.019
		EG34	0.970
		EG14	0.863
		EG37	0.657

If we consider only the highest metric bins for all metrics, the highest utility that could be obtained by any Evaluation Group is 1.00 and this was defined as the highest benefit utility achieved threshold. Evaluation Groups that have this value are all continuous recycle options with the exception of EG06, EG07, EG08, and EG09; these four Evaluation Groups are in the set because of their very high fuel burnups.

In Appendix D-2.15, it was noted that the Basis of Comparison (EG01) is in bin A for the natural thorium required metric, as it requires no thorium. For the purpose of comparison by metric data, no other group can perform better than it. In fact, note that 38 of the 40 Evaluation Groups are in bin A for the natural thorium required metric. However for the natural uranium required metric, the Basis of Comparison is in bin D and so can be improved upon. Threshold 1 was defined by considering Bin B of the natural uranium required metric, and Bin A for natural thorium required, as shown in Table E-6.5. This yields a utility of 0.608 (0.408 better than the Basis of Comparison). This adds the Evaluation Groups EG04, EG10, EG14, and EG37 to the list above.

As noted above, the Evaluation Groups that meet each threshold were ranked using the ratio of incremental benefit (the increase in resource utilization utility for the Evaluation Group over the resource utilization utility for the Basis of Comparison) to incremental challenge as an indication of promise. The ordered list of Evaluation Groups based on this ratio is summarized in Table E-6.6 for each of the thresholds defined above.

E-6.2 Sensitivity Analysis

There are 8 unique combinations of shape functions and metric tradeoff factors that were considered in evaluating and ranking Evaluation Groups on the Resource Utilization Criterion. The combinations were examined for logical consistency, and exploratory analyses were conducted to reduce this set (if possible) to a smaller set that would still capture any significant differences between ranking and evaluation results. Exploratory analyses also showed that the results considering a combination of logarithmic shape function for the Natural Uranium Required metric with a linear shape function for the Natural Thorium Required (and vice versa) always lay between the results combining either the log shape functions or linear shape function, and thus the bounding sets should be sufficient for exploring the implications of the result.

These simplifications reduced the number of combinations required for scenario analysis to represent the range of perspectives on Resource Utilization in this study from 8 to 4 (two combinations of shape functions with 2 metric tradeoff factor sets).

The resulting data for the 4 combinations are shown in Figure E-6.4 and Table E-6.7. The figure shows the calculated utility value on the Resource Utilization considering the two metrics, using the shape functions and metric tradeoff factors specified; the table shows the same values, with the Evaluation Groups sorted by utility value for each set of shape functions and metric tradeoff factors. The utility scale ranges from 0 to 1, across the range of bins for the metrics: an Evaluation Group would have to be in the best performing bin on the two metrics to have a Resource Utilization utility of 1, and would have to be in the worst performing bin on all five metrics to have a utility value of 0.

Table E-6.7. Resource Utilization Criterion Sensitivity Analysis Results with Different Shape Functions and Trade-off Factors.

Shape Functions								
Natural Uranium Required		1		2		1		2
Natural Thorium Required		1		2		1		2
Tradeoff Factor Set		1		1		2		2
	EG06	1.000	EG06	1.000	EG06	1.000	EG06	1.000
	EG07	1.000	EG07	1.000	EG07	1.000	EG07	1.000
	EG08	1.000	EG08	1.000	EG08	1.000	EG08	1.000
	EG09	1.000	EG09	1.000	EG09	1.000	EG09	1.000
	EG23	1.000	EG23	1.000	EG23	1.000	EG23	1.000
	EG24	1.000	EG24	1.000	EG24	1.000	EG24	1.000
	EG26	1.000	EG26	1.000	EG26	1.000	EG26	1.000
	EG28	1.000	EG28	1.000	EG28	1.000	EG28	1.000
	EG29	1.000	EG29	1.000	EG29	1.000	EG29	1.000
	EG30	1.000	EG30	1.000	EG30	1.000	EG30	1.000
	EG33	1.000	EG33	1.000	EG33	1.000	EG33	1.000
	EG34	1.000	EG34	1.000	EG34	1.000	EG34	1.000
	EG38	1.000	EG38	1.000	EG38	1.000	EG38	1.000
	EG40	1.000	EG40	1.000	EG40	1.000	EG40	1.000
	EG04	0.755	EG04	0.960	EG10	0.902	EG10	0.984
	EG10	0.755	EG10	0.960	EG04	0.608	EG04	0.936
	EG14	0.755	EG14	0.960	EG14	0.608	EG14	0.936
	EG37	0.755	EG37	0.960	EG37	0.608	EG37	0.936
	EG11	0.595	EG11	0.795	EG11	0.352	EG11	0.672
	EG12	0.595	EG12	0.795	EG12	0.352	EG12	0.672
	EG19	0.595	EG19	0.795	EG19	0.352	EG19	0.672
	EG20	0.595	EG20	0.795	EG20	0.352	EG20	0.672
	EG25	0.595	EG25	0.795	EG25	0.352	EG25	0.672
	EG31	0.595	EG31	0.795	EG31	0.352	EG31	0.672
	EG32	0.595	EG32	0.795	EG32	0.352	EG32	0.672
	EG39	0.595	EG39	0.795	EG39	0.352	EG39	0.672
	EG01	0.500	EG01	0.500	EG01	0.200	EG01	0.200
	EG02	0.500	EG02	0.500	EG02	0.200	EG02	0.200
	EG03	0.500	EG03	0.500	EG03	0.200	EG03	0.200
	EG13	0.500	EG13	0.500	EG13	0.200	EG13	0.200
	EG15	0.500	EG15	0.500	EG15	0.200	EG15	0.200
	EG16	0.500	EG16	0.500	EG16	0.200	EG16	0.200
	EG17	0.500	EG17	0.500	EG17	0.200	EG17	0.200
	EG18	0.500	EG18	0.500	EG18	0.200	EG18	0.200
	EG21	0.500	EG21	0.500	EG21	0.200	EG21	0.200
	EG22	0.500	EG22	0.500	EG22	0.200	EG22	0.200
	EG27	0.500	EG27	0.500	EG27	0.200	EG27	0.200
	EG35	0.500	EG35	0.500	EG35	0.200	EG35	0.200
	EG36	0.500	EG36	0.500	EG36	0.200	EG36	0.200
	EG05	0.255	EG05	0.460	EG05	0.102	EG05	0.184

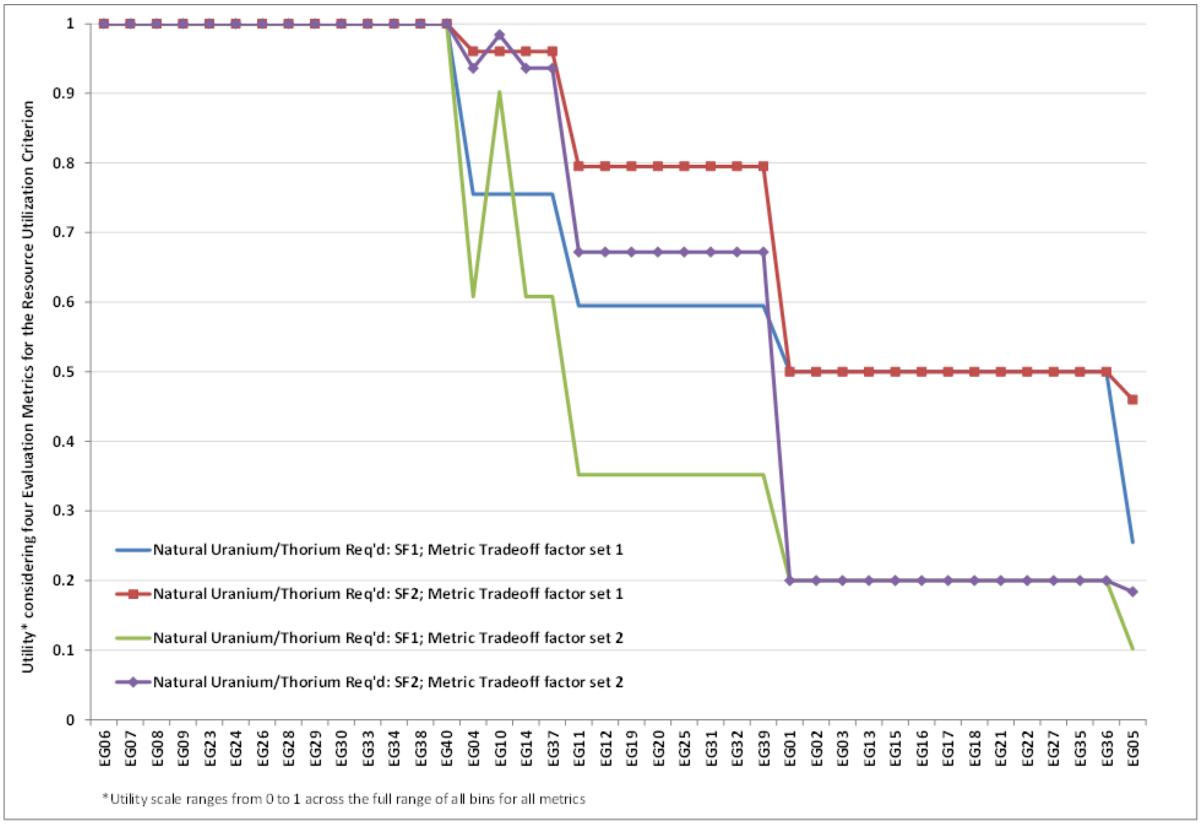

Figure E-6.4. Resource Utilization Criterion Sensitivity Analysis Results with Different Shape Functions and Trade-off Factors.

The sensitivity analysis results show that there are four distinct set of Evaluation Groups in which the members of each set mostly cluster together. The primary impacts of the different combinations of shape functions and tradeoff factors are in the magnitudes of the calculated utilities for the Evaluation Groups; the ordering and clusters of Evaluation Groups is the same for all four perspectives. As one would expect, the fourteen Evaluation Groups identified above also consistently have a utility of 1.0 and would give the highest benefit with respect to this criterion.

It is interesting to note that this is mostly the same set of Evaluation Groups that appear in Bin A of the natural uranium required metric in Appendix D-2.14. The only exception is the absence of EG10 in the cluster listed above. This is because EG10 uses thorium and is one of the only two Evaluation Groups that are in bin B for the *natural thorium required* metric (Appendix D-2.15). Based on the analysis in Appendix D-2.14, it is evident that these 14 Evaluation Groups are high scoring for this criterion because their primary fuel cycle characteristics are continuous recycle options, or a few with higher burnup of fuel with or without enrichment support, or thorium-only options.

The Evaluation Groups in the next lower performance set include EG04, EG10, EG14, and EG37.

- EG04 - Once-through using 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
- EG14 - Limited recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors
- EG37 - Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in both fast and thermal critical reactors.

The impact of thorium on this classification of Evaluation Groups into the resulting clusters is quite limited. This is because nearly all the Evaluation Groups (except EG05 and EG10) are in bin A under the natural thorium required metric (see Appendix D-2.15).

E-6.3 Summary: Characteristics of Promising Groups

From these results it is observed that:

- At the equilibrium state, options using enriched uranium fuel require significantly higher amount of natural uranium resource than options not using enrichment. These options are typically those with external internal conversion (or breeding).
- Even in Th/U fueled options in which fissile uranium is used to support the thorium fuel, the uranium requirement dominates the natural resource requirement and the amount is generally significant.
- Options requiring relatively small amounts of natural uranium or thorium are those that are:
  - Continuous recycle options not needing enriched uranium in the equilibrium state (whether thorium only or uranium only).
  - Options with high fuel burnup not requiring enriched uranium fuels also performed well; reactors can get to about less than 30% burnup under certain assumptions and EDS (specifically FFH) systems can get to higher burnup (>70%) under some assumptions; both performing well but the EDS/FFH even better (in highest Bin for the metric).
- The *basis of comparison* EG01 is consistently in the lowest quartile for this criterion.

Potential Supporting R&D Indicated by Results for Resource Utilization Criterion

Based on the identified Evaluation Groups above, arising from the conditional statements on promising options, following are the R&D activities that have been identified:

- Separation technologies for the limited and continuous recycle options
- Extremely high burnup fuels (>30%) required for options with no enrichment and no fuel separations
  - Primarily, advanced cladding materials that can withstand high irradiation levels at reactor temperatures
  - Fuel that can retain or safely release fission products from high burnup fuels
- Recycle fuels
- Advanced reactors
  - Fast-spectrum reactor and liquid fuel reactor (e.g., MSR) options
  - Reactor systems with conversion ratio greater than 1
  - Breed and burn reactor concepts that utilize high burnup fuels
- Externally-driven systems utilizing extremely high burnup fuels
  - For very high burnup with no initial enrichment, fusion-fission hybrid system is desirable for high performance.
  - Thorium mining, milling, and fuel processing and preparation technologies to implement options using thorium.

E-7. Development and Deployment Risk

The Development and Deployment Risk Criterion considers those challenges to develop a fuel cycle system and bring it to the level of commercial viability. It is informed by six Metrics.

- Development time
- Development cost
- Deployment cost from prototypic validation to FOAK commercial
- Compatibility with the existing infrastructure
- Existence of regulations for the fuel cycle and familiarity with licensing
- Existence of market incentives and/or barriers to commercial implementation of fuel cycle processes

The Metric Data for these Metrics for all 40 Evaluation Groups are provided in Appendix D, along with observations on individual Metrics. This data is also presented in Figure E-7.1, which includes a line that shows that no Evaluation Group exceeds the Basis of Comparison (EG01). Therefore, none of the Evaluation Groups would be expected to rank higher than the Basis of Comparison for the Development and Deployment Risk Criterion.

Other than the Basis of Comparison, no other Evaluation Group outperforms all others based on Metric Data alone, so informing on the relative overall Development and Deployment Risk for the Evaluation Groups requires combining the Metric Data through the use of shape functions to provide a utility for each Evaluation Metrics and metric tradeoff factors to combine utilities to obtain a utility for the Development and Deployment Risk Criterion.

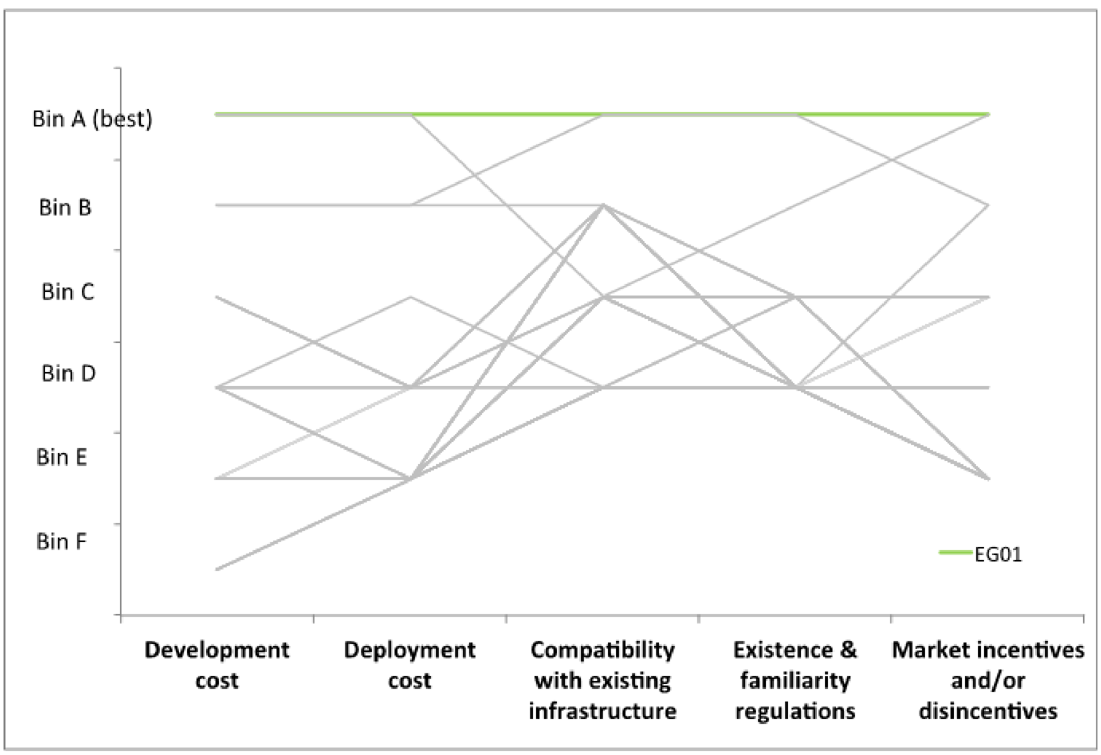

Figure E-7.1. Metric Data for Evaluation Metrics for the Development and Deployment Risk.

E-7.1 Shape Functions and Metric Tradeoff Factors for Development and Deployment Risk Metrics

For each of the Development and Deployment Risk Metrics, one or more shape functions were developed using the process described in Appendix A. The shape functions for these Metrics are presented in Figures E-7.2 through E-7.6 and the perspectives represented by those different shape functions are described below.

Development time and cost combined shape functions

For the purpose of informing on Development and Deployment Risk, two Metrics, Development Time and Development Cost, are considered together, as it is difficult to consider the relative value of changes in one without considering the other Metric. For example, the relative value of reducing the development time from 5-10 years to less than 5 years is different if the development costs are >$25B than if they are <$200M. In the terminology of multi-attribute utility analysis discussed in Appendix A, these two metrics are considered preferentially *dependent*, and thus should not be combined in a weighted additive utility model with the other 4 metrics. To account for this dependence, the two metrics are considered together using a combined shape function.

Shape Function 1	No development needed	< 5 yrs	5-10 yrs	10-25 yrs	25-50 yrs	> 50 yrs
No development needed	100%	97%	90%	77%	50%	0%
<$200M	99.7%	96%	90%	76%	50%	0%
$200M - $2B	97%	94%	87%	74%	49%	0%
$2B - $10B	84%	81%	76%	64%	42%	0%
$10B - $25B	53%	52%	48%	41%	27%	0%
> $25B	0%	0%	0%	0%	0%	0%

Shape Function 2	No development needed	< 5 yrs	5-10 yrs	10-25 yrs	25-50 yrs	> 50 yrs
No development needed	100%	80%	60%	40%	20%	0%
<$200M	80%	64%	48%	32%	16%	0%
$200M - $2B	60%	48%	36%	24%	12%	0%
$2B - $10B	40%	32%	24%	16%	8%	0%
$10B - $25B	20%	16%	12%	8%	4%	0%
> $25B	0%	0%	0%	0%	0%	0%

Figure E-7.2. Combined Shape Functions for the Development Time and Cost Metrics.

Shape Function 1: This shape function represents the perspective that the relative value of a change in development time or a change in development cost is directly proportional to the size of that change. That is, "a dollar is a dollar and a year is a year."

Shape Function 2: This shape function represents the perspective that there are time and cost barriers, as defined by the bin boundaries, that present significantly more or less challenge in developing a technology, so the value of crossing one of those thresholds (of moving from one bin to another) is constant. This may represent, for example, barriers associated with governmental or organization project and program approval levels and funding constraints.

Deployment cost from prototypic validation to FOAK Commercial shape functions

Shape Function 1: This shape function represents the perspective that the relative value of a change in deployment cost is directly proportional to the size of that change: that is, "a dollar is a dollar."

Shape Function 2: This shape function represents the perspective that there are cost barriers, as defined by the bin boundaries, that present significantly more or less challenges in deploying a technology, so that the value of crossing those thresholds (of moving from one bin to another) is constant. This may represent, for example, barriers associated with governmental or organization project and program approval levels and funding constraints.

Shape Function 3: This shape function is similar to the deployment cost shape function 2, but considers the development cost in excess of \$25B to represent the highest challenge rather than the > \$50B value used in shape function 1, with the perspective that the there is no difference between > \$25B and > \$50B in terms of deployment cost challenge.

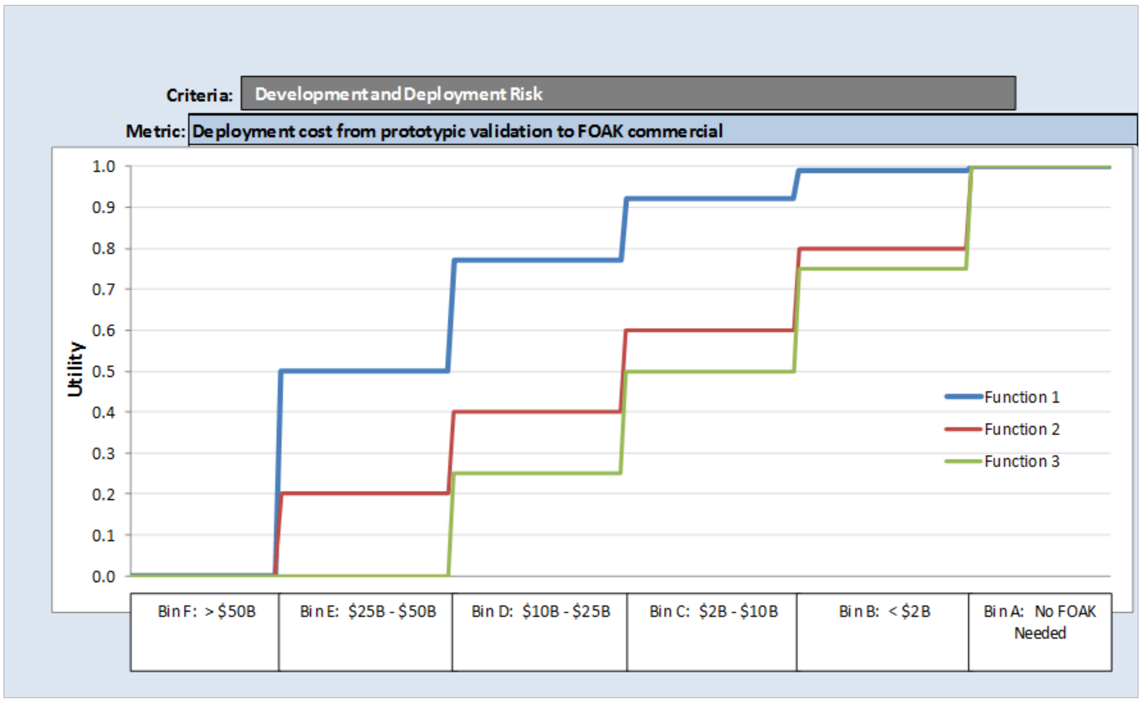

Figure E-7.3. Shape Functions for Deployment Cost from Prototypic Validation to FOAK Commercial Metric.

Compatibility with existing infrastructure shape functions

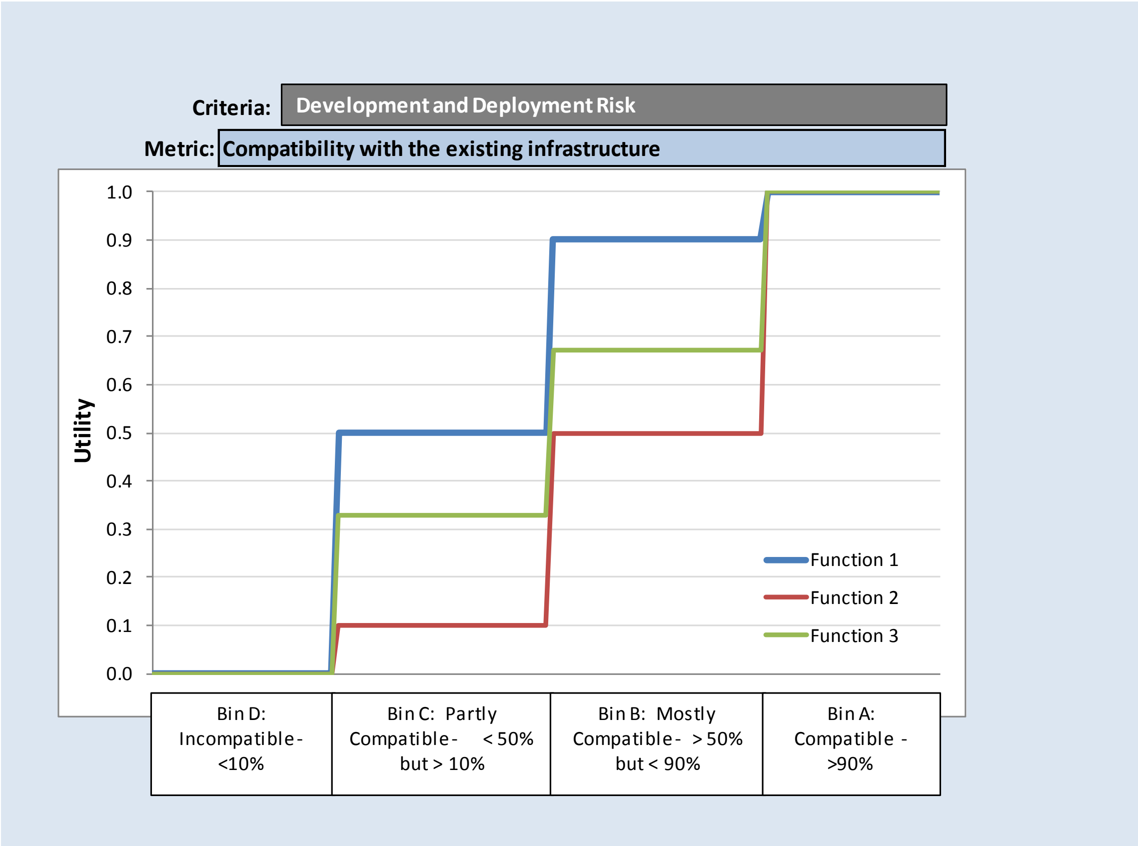

Figure E-7.4. Shape Functions for Compatibility with the Existing Infrastructure Metric.

Shape Function 1: This shape function represents the perspective that the largest change in value is associated with decreasing the amount of new infrastructure required from a high level (90% of required infrastructure is new) to a lower level.

Shape Function 2: This shape function represents the perspective that the largest change in relative value for a fuel cycle is associated with decreasing the amount of new infrastructure required to low level (10% or less of the required infrastructure must be new).

Shape Function 3: This shape function represents the perspective that the relative value of changes in compatibility with existing infrastructure is directly proportional to the amount of new infrastructure required ranging from nearly all new infrastructure to nearly no new infrastructure.

Existence of regulations for the fuel cycle and familiarity with licensing shape functions

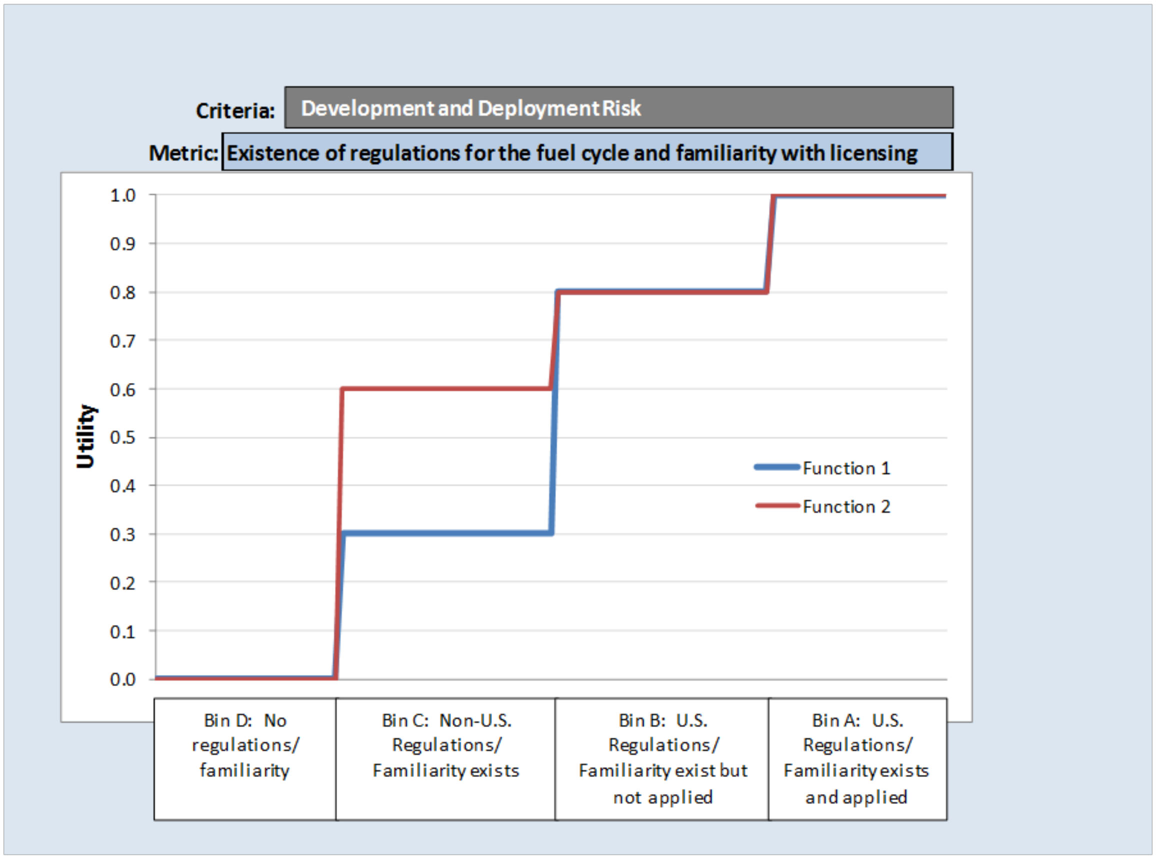

Figure E-7.5. Shape Functions for Existence of Regulations for the Fuel Cycle and Familiarity with Licensing Metric.

Shape Function 1: This shape function represents the perspective that the most valuable change with regard to the existence of regulation and familiarity with licensing comes from having US regulations and familiarity (rather than simply having regulations in other countries). Less emphasis is placed on value gained by the regulations being demonstrated and applied through licensing actions in the U.S. This perspective considers it to be a larger challenge to establish U.S. regulations even if international regulations exist.

Shape Function 2: This shape function represents the perspective that the most valuable change with regard to the existence of regulations and familiarity with licensing comes from in having *any* regulations and familiarity, even outside the US, as compared to having no regulations or familiarity. This perspective suggests that that having once established the regulations internationally, that experience can be used to inform the U.S. regulatory processes.

Existence of market incentives and/or barriers to commercial implementation of fuel cycle processes shape functions

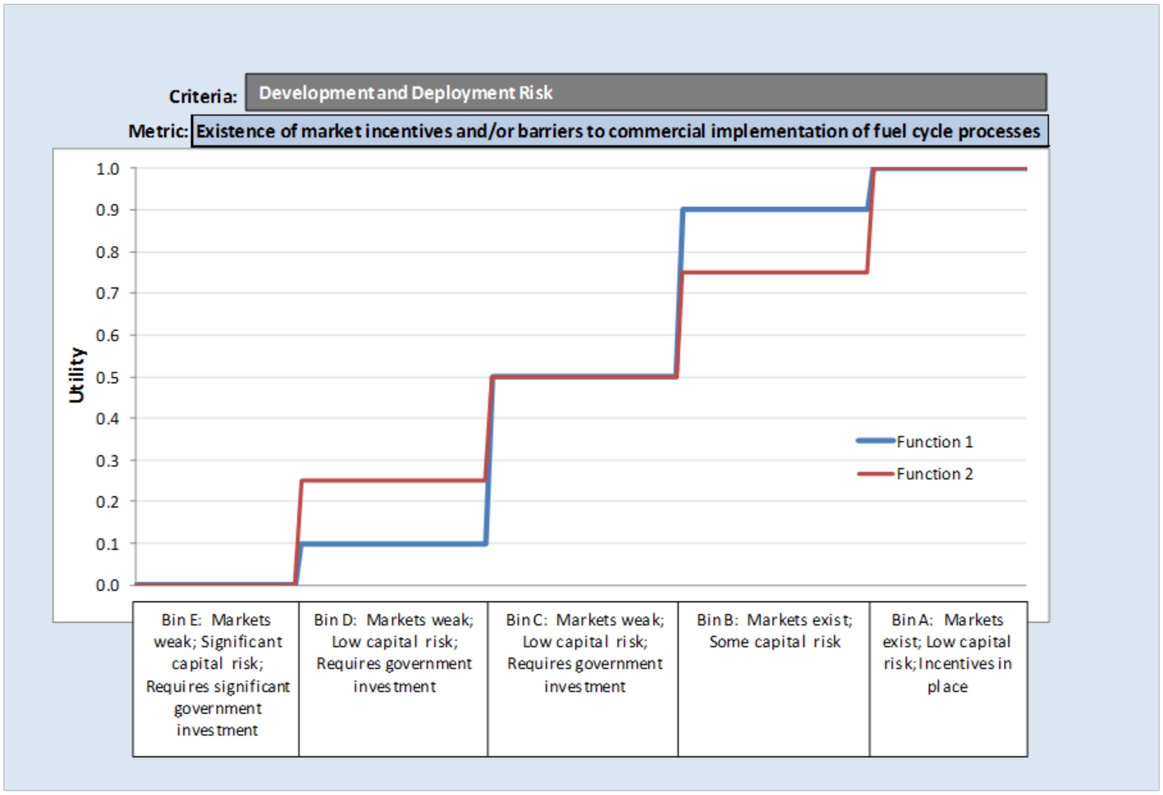

Figure E-7.6. Shape Functions for Existence of Market Incentives and/or Barriers to Commercial Implementation of Fuel Cycle Processes Metric.

Shape Function 1: This shape function reflects a perspective that values changes in the market conditions supporting or inhibiting fuel cycle implementation, which are emphasized in Bins B, C, and D, more strongly than changes in the amount of capital at risk alone, which are emphasized in the differences between Bins A and B, and between Bins D and E.

Shape Function 2: This shape function reflects a perspective that places roughly equal emphasis on change in the market conditions supporting or inhibiting fuel cycle implementation and factors associated with the amount of capital at risk.

To generate a combined utility value for this Criterion, the utility values obtained for each metric using their corresponding shape functions are combined using metric trade-off factors that reflect a relative importance of changes in one metric relative to changes in the other. The trade-off factor sets for this criterion are presented in Table E-7.1.

Trade-off Factor set 1: This trade-off factor set emphasizes changes in the time and cost associated with the research and development to achieve a technology readiness level of 6 (pilot scale demonstration). The trade-off factor set places less emphasis on changes in deployment cost and institutional issues. This trade-off factor may represent the perspective of an organization performing research and development activities.

Trade-off Factor set 2: Trade-off factor set 2 reflects an emphasis on changes in the two factors most directly tied to the costs and difficulties of deployment: deployment costs and compatibility with existing fuel cycle technology (similar to that included in the Basis of Comparison). The trade-off factor set places less emphasis on changes in development time and cost, and the other institutional issues that may impede full-scale implementation. This trade-off factor set may represent the perspective of an organization interested in deploying fuel cycle technologies and leveraging investments in existing infrastructure.

Trade-off Factor set 3: Trade-off factor set 3 reflects a strong emphasis on changes in the institutional issues related to full-scale implementation of a fuel cycle, with a secondary emphasis on changes in the costs to deployment a FOAK system, and de-emphasizes changes in development time and cost. The trade-off factor set places roughly equal emphasis on changes in each of the three institutional issues (use of existing infrastructure, regulatory familiarity, and market incentives and barriers). This trade-off factor set may represent the perspective of an organization interested in taking fuel cycles that have been demonstrated and deploying them all the way through full-scale implementation.

Trade-off Factor set 4: Trade-off factor set 4 reflects an emphasis of bringing a technology through the development state to the deployment of a first of a kind system. The primary emphasis is on changes in development time and cost and deployment costs, with roughly equal value for a dollar reduction in cost, whether it be a “development dollar” or a “deployment dollar.” This trade-off factor set reflects emphasis on changes in institutional issues that may impede implementation of the fuel cycle. This trade-off factor set may represent the perspective of an organization developing technology up to the point of initial deployment.

Trade-off Factor set 5: Trade-off factor set 5 places roughly equal emphasis on changes in the development time and cost, changes in deployment costs, and changes in the institutional issues that may impede fuel cycle implementation. Among the institutional issues, this tradeoff factor set emphasizes changes in the market incentives and barriers. Similar to trade-off set 4, this trade-off factor set may represent the perspective of an organization developing technology up to the point of deployment, but in this case also includes an increased consideration of market support for the technology that would facilitate full-scale implementation.

Table E-7.1. Trade-off factor sets for the Development and Deployment Risk Criterion.

	Metric tradeoff factors representing the relative importance of changes in each metric, considering the entire range defined by the bins for each metric				
Metric	**Factor Set 1**	**Factor Set 2**	**Factor Set 3**	**Factor Set 4**	**Factor Set 5**
Development time and cost	0.5	0.1	0	0.25	0.3
Deployment cost from prototypic validation to FOAK commercial	0.25	0.25	0.25	0.45	0.3
Compatibility with the existing infrastructure	0.1	0.45	0.25	0.1	0.05
Existence of regulations for the fuel cycle and familiarity with licensing	0.1	0.1	0.25	0.05	0.05
Existence of mark incentives and/or barriers to commercial implementation of fuel cycle processes	0.05	0.1	0.25	0.15	0.3

E-7.2 Initial Sensitivity Analysis

The shape functions and trade-off factor sets described above results in a total of 360 possible combinations. However, not all of these combinations have consistent perspectives and not all of the shape function/trade-off factor set combinations result in unique rankings of Evaluation Groups. In order to obtain a tractable set of combinations of shape functions and trade-off factor sets for evaluation and screening, an exploratory analysis of these combinations were performed. This led to a reduction to a total of 12 combinations that preserve the overall variation among the original combinations.

This reduction was made by comparing Evaluation Group utility values and rankings at the Criterion level, and based on the following observations:

1. The shape functions for development time and cost and deployment cost should be based on the same perspective regarding how cost is considered, either linear in cost or linear in the bin structure.
2. For Compatibility with the Existing Infrastructure Metric, one of the three shape function lies entirely in between the other two, so only the two bounding shape functions (1 & 2) were retained.
3. Review of the combined utility value and rankings at the Criterion level showed little sensitivity to:
    a. the shape function for Market Incentives and/or Barriers to Commercial Implementation of Fuel Cycle Processes, so one function was chosen to represent both perspectives.
    b. the shape function for Deployment Cost, so one function was chosen to represent both perspectives (Shape Function 2).
    c. the shape function for the Existence of Regulations for the Fuel Cycle and Familiarity with Licensing, so one function was retained (Shape Function 1)
4. Trade-off factors sets 1, 4, and 5 gave very similar results, such that only one of these three sets needs to be retained, reducing the number of trade-off factor sets to 3 (reduction to 12 combinations).

E-7.3 Results for the Development and Deployment Risk Criterion

The ranking of Evaluation Groups by the utility representing Development and Deployment Risk for the 12 combinations of shape functions and metric tradeoff factors are shown in Table E-7.2.

Several observations are consistent across all 12 perspectives considered:

- At the criterion level, the Basis of Comparison (EG01) is always the highest ranked fuel cycle Evaluation Group across all tradeoff factor sets. This would be expected because this fuel cycle option is currently deployed and therefore has the lowered development and deployment risk; as shown above, it has the best metric data possible for all six metrics.
- Evaluation Groups that consist of once-through fuel cycles that use existing reactor types are consistently ranked very high. This includes fuel cycles that can use existing reactor types with higher burnup uranium fuels (EG02), fuel cycles using natural uranium fuels (EG03), and once-through fuel cycles that use uranium and thorium fuels in a thermal reactor (EG05).
- The highest ranked limited recycle fuel cycle Evaluation Groups are those that recycle Pu in thermal reactors. This includes EG12, EG13, and EG15 that are predominately ranked in the top quartile of fuel cycle Evaluation Groups.

- The highest ranked single stage continuous recycle Evaluation Groups recycle Pu in a thermal reactor (EG19, EG21)
- The lowest ranked fuel cycles are predominately continuous recycle single stage and multi-stage fuel cycles that involve TRU and/or U-233 recycle.
- The highest ranked EDS fuel cycle Evaluation Groups are once-through fuel cycles using uranium or thorium and predominately rank in the middle of the Evaluation Group rankings.
- The highest ranking fuel cycle Evaluation Group that uses thorium is a once-through fuel cycle using U/Th in a thermal reactor (EG05). This Evaluation Group consistently ranked in the top 10%.
- Fuel cycle Evaluation Groups that involve continuous recycle of thorium are generally ranked in the lower half of all Evaluation Groups.

Differences between the Evaluation Groups rankings across the 12 perspectives highlight an additional observation:

- Evaluation Groups that use reactor types that are not currently commercially deployed (such as fast reactors and EDS) require greater development costs, longer development time, and are less compatible with existing infrastructure than do Evaluation Groups with existing, deployed reactor systems. Accordingly, those requiring new reactor types perform well with respect to this Criterion only for perspectives that place less emphasis on those metrics.

The Development and Deployment Risk Criterion is a “challenge” criterion and therefore does not directly inform on promising Evaluation Groups. However, during development of the metric data, research needs were identified based on the use of fuel cycle processes for the Development Time and Cost metrics. For Evaluation Groups considered to be promising based on the results of other criteria, this list of research needs for the fuel cycle processes used for the Development and Deployment Risk metrics (see Appendix C) should be considered.

In subsequent analyses where multiple criteria are considered, both the Benefit and the Challenge for each Evaluation Group are considered simultaneously (see other sections within Appendix E, and Appendix F). For clarity of discussion and presentation, the utility values for Development and Deployment risk from the first column of Table E-7.2 are used as the set representing Challenge. In all cases, sensitivity analyses are presented that consider the set of 12 different perspectives discussed above.

Table E-7.2. Evaluation Group Ranking Results for the Development and Deployment Risk Criterion.

Shape Functions												
Development Time and Cost	1	1	2	2	1	1	2	2	1	1	2	2
Depolyment Cost	1	1	2	2	1	1	2	2	1	1	2	2
Compatibilty with Existing Infrastru	1	2	1	2	1	2	1	2	1	2	1	2
Existence of Regulations	1	1	1	1	1	1	1	1	1	1	1	1
Market Barriers/Incentives	1	1	1	1	1	1	1	1	1	1	1	1
Trade-off Factor Set	1	1	1	1	2	2	2	2	3	3	3	3
	EG01	EG01	EG01	EG01	EG01	EG01	EG01	EG01	EG01	EG01	EG01	EG01
	EG02	EG02	EG03	EG03	EG02	EG02	EG02	EG02	EG02	EG02	EG02	EG02
	EG03	EG03	EG02	EG02	EG05	EG05	EG05	EG05	EG03	EG03	EG03	EG03
	EG05	EG05	EG05	EG05	EG13	EG13	EG03	EG03	EG05	EG05	EG05	EG05
	EG13	EG13	EG13	EG13	EG21	EG21	EG13	EG13	EG13	EG13	EG13	EG13
	EG21	EG21	EG21	EG21	EG03	EG03	EG21	EG21	EG21	EG21	EG21	EG21
	EG12	EG12	EG12	EG12	EG15	EG15	EG15	EG15	EG12	EG04	EG12	EG04
	EG19	EG19	EG19	EG19	EG17	EG17	EG17	EG17	EG19	EG12	EG19	EG12
	EG15	EG04	EG15	EG04	EG12	EG12	EG18	EG18	EG15	EG19	EG15	EG19
	EG04	EG15	EG04	EG15	EG19	EG19	EG22	EG22	EG04	EG15	EG04	EG15
	EG31	EG31	EG31	EG31	EG18	EG18	EG16	EG16	EG31	EG06	EG17	EG06
	EG23	EG23	EG17	EG23	EG22	EG22	EG35	EG35	EG17	EG07	EG18	EG07
	EG17	EG17	EG14	EG17	EG16	EG16	EG36	EG36	EG18	EG08	EG22	EG08
	EG14	EG14	EG23	EG14	EG35	EG35	EG39	EG39	EG22	EG31	EG31	EG17
	EG29	EG29	EG29	EG29	EG36	EG04	EG40	EG40	EG16	EG17	EG16	EG18
	EG18	EG06	EG18	EG06	EG39	EG36	EG12	EG12	EG35	EG18	EG35	EG22
	EG22	EG07	EG22	EG07	EG40	EG39	EG19	EG19	EG36	EG22	EG36	EG31
	EG06	EG08	EG16	EG08	EG31	EG40	EG31	EG04	EG39	EG23	EG39	EG16
	EG07	EG18	EG35	EG18	EG14	EG31	EG14	EG31	EG40	EG16	EG40	EG23
	EG08	EG22	EG06	EG22	EG29	EG23	EG29	EG06	EG14	EG35	EG14	EG35
	EG16	EG16	EG07	EG16	EG20	EG06	EG20	EG07	EG29	EG36	EG29	EG36
	EG35	EG35	EG08	EG35	EG30	EG07	EG30	EG08	EG06	EG39	EG06	EG39
	EG20	EG20	EG20	EG20	EG32	EG08	EG32	EG23	EG07	EG40	EG07	EG40
	EG30	EG30	EG30	EG30	EG33	EG14	EG33	EG14	EG08	EG14	EG08	EG14
	EG32	EG32	EG32	EG32	EG37	EG29	EG37	EG29	EG20	EG29	EG20	EG29
	EG33	EG33	EG33	EG33	EG38	EG20	EG38	EG20	EG23	EG20	EG23	EG20
	EG37	EG37	EG36	EG36	EG04	EG30	EG34	EG30	EG30	EG30	EG30	EG30
	EG38	EG38	EG37	EG37	EG34	EG32	EG04	EG32	EG32	EG32	EG32	EG32
	EG09	EG09	EG38	EG38	EG23	EG33	EG06	EG33	EG33	EG33	EG33	EG33
	EG10	EG10	EG39	EG39	EG06	EG37	EG07	EG37	EG34	EG34	EG34	EG34
	EG11	EG11	EG40	EG40	EG07	EG38	EG08	EG38	EG37	EG37	EG37	EG37
	EG24	EG24	EG34	EG09	EG08	EG34	EG23	EG34	EG38	EG38	EG38	EG38
	EG25	EG25	EG09	EG10	EG09	EG09	EG09	EG09	EG09	EG09	EG09	EG09
	EG26	EG26	EG10	EG11	EG10	EG10	EG10	EG10	EG10	EG10	EG10	EG10
	EG27	EG27	EG11	EG24	EG11	EG11	EG11	EG11	EG11	EG11	EG11	EG11
	EG28	EG28	EG24	EG25	EG24	EG24	EG24	EG24	EG24	EG24	EG24	EG24
	EG36	EG36	EG25	EG26	EG25	EG25	EG25	EG25	EG25	EG25	EG25	EG25
	EG39	EG39	EG26	EG27	EG26	EG26	EG26	EG26	EG26	EG26	EG26	EG26
	EG40	EG40	EG27	EG28	EG27	EG27	EG27	EG27	EG27	EG27	EG27	EG27
	EG34	EG34	EG28	EG34	EG28	EG28	EG28	EG28	EG28	EG28	EG28	EG28

E-8. Institutional Issues

As discussed in Appendix C, the Institutional Issues Criterion considers societal and infrastructure issues that may help or hinder implementation, for this study focusing on industry infrastructure, market mechanisms, and regulatory framework. It is informed by the following three Metrics:

- Compatibility with the existing infrastructure
- Existence of regulations for the fuel cycle and familiarity with licensing
- Existence of market incentives and/or barriers to commercial implementation of fuel cycle processes

As discussed in Appendix C, this Criterion and the supporting Metrics are included in the Development and Deployment Risk Criterion. The Metric Data for these Metrics for all 40 Evaluation Groups are provided in Appendix D, along with observations on the individual Metrics. This data is also presented in Figure E-8.1, which includes a line that shows that no Evaluation Group exceeds the Basis of Comparison

(EG01). Therefore, none of the Evaluation Groups would be expected to rank higher than the basis of comparison for the Institutional Issues Criterion.

Other than the Basis of Comparison, no other Evaluation Group outperforms others on all the Metric Data, so informing on the overall Criterion level requires combining Metric Data through the use of shape functions and metric tradeoff factors

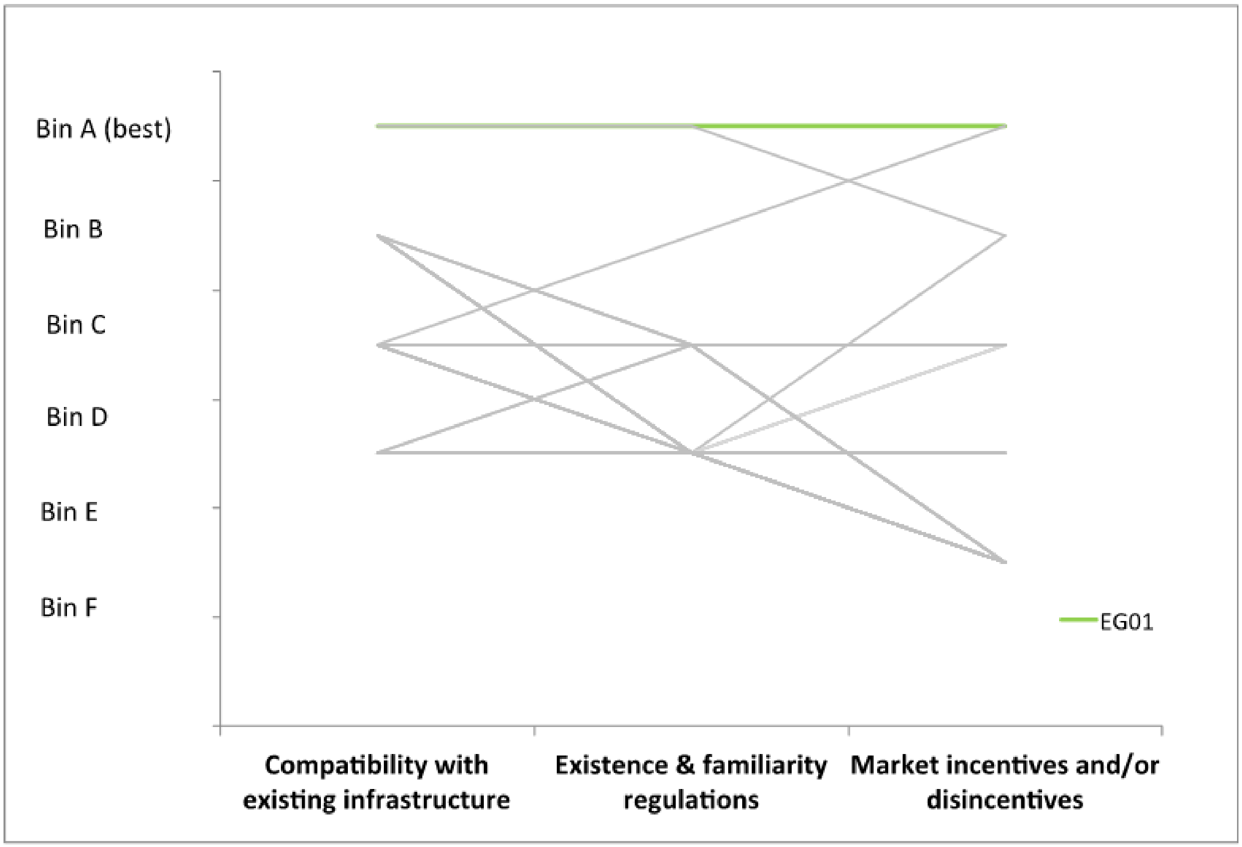

Figure E-8.1. Metric Data for Evaluation Metrics for the Institutional Issues.

E-8.1 Shape Functions and Metric Tradeoff Factors for Institutional Issues Metrics

The shape functions for the Institutional Issues Metrics are described in Section E-7.1 and the same perspectives apply here. The metric trade-off factor sets are also consistent with those used for the Development and Deployment Risk Criterion and are provided in Table E-8.1. The trade-off factor set values correspond to the Institutional Issue Metrics in Table E-7.1, renormalized to a sum of unity. Note that in doing so, the renormalization of Trade-off Factor sets 1 and 2 in Table E-7.1 result in the same metric- tradeoff factors for the Institutional Issues metrics, and therefore Trade-off factor set 1 has been excluded from the trade-off factor sets for Institutional Issues.

Table E-8.1. Trade-off Factor Sets for the Institutional Issues Criterion.

	Metric tradeoff factors representing the relative importance of changes in each metric, considering the entire range defined by the bins for each metric			
Metric	**Factor Set 1**	**Factor Set 2**	**Factor Set 3**	**Factor Set 4**
Compatibility with the existing infrastructure	0.15	0.4	0.7	0.33
Existence of regulations for the fuel cycle and familiarity with licensing	0.15	0.4	0.15	0.33
Existence of mark incentives and/or barriers to commercial implementation of fuel cycle processes	0.7	0.2	0.15	0.34

E-8.2 Initial Sensitivity Analysis

The Institutional Issues Criterion contains a total of 48 combinations of shape functions and metric trade-off factor sets. The same considerations as used in Development and Deployment Risk were used to reduce the number of combinations, resulting in a total of 8 combinations that represented the variability of all 48 combinations:

- Compatibility with the existing infrastructure is represented with Shape Functions 1 and 2, which bound the third shape function.
- Based on the insensitivity of the calculated utility values and Evaluation Group rankings, Existence of Regulations for the Fuel Cycle and Familiarity with Licensing Metric is represented with Shape Function 1 only
- Based on the insensitivity of the calculated utility values and Evaluation Group rankings, Market Incentives and/or Barriers to Commercial Implementation of Fuel Cycle Processes is represented with Shape Function 1 only
- Trade-off factor sets 1 through 4 are retained.

E-8.3 Results for the Institutional Issues Criterion

The ranking of Evaluation Groups by the utility representing Institutional Issues for the 8 combinations of shape functions and metric tradeoff factors are shown in Table E-8.2. The overall rankings and variability is similar to that of the Development and Deployment Risk Criterion, with the Basis of Comparison (EG01) having the top ranking. The overall observations on the ranking of the Evaluation Groups are similar to that for Development and Deployment Risk and are not repeated here, being summarized in Section E-7.3.

Table E-8.2. Evaluation Group Ranking Results for the Institutional Issues Criterion.

Shape Functions								
Compatibility with Existing Infrastructure	1	2	1	2	1	2	1	2
Existence of Regulations	1	1	1	1	1	1	1	1
Market Barriers/Incentives	1	1	1	1	1	1	1	1
Trade-off Factor Set	1	1	2	1	2	3	4	4
	EG01	EG01	EG01	EG01	EG01	EG01	EG01	EG01
	EG02	EG02	EG02	EG02	EG02	EG02	EG02	EG02
	EG03	EG03	EG03	EG03	EG05	EG05	EG03	EG03
	EG05	EG05	EG13	EG13	EG13	EG13	EG05	EG05
	EG13	EG13	EG21	EG21	EG21	EG21	EG13	EG13
	EG21	EG21	EG05	EG05	EG15	EG15	EG21	EG21
	EG12	EG12	EG15	EG15	EG17	EG17	EG12	EG12
	EG19	EG19	EG12	EG12	EG18	EG18	EG19	EG19
	EG04	EG04	EG19	EG19	EG22	EG22	EG15	EG04
	EG06	EG06	EG17	EG17	EG16	EG16	EG17	EG15
	EG07	EG07	EG18	EG18	EG35	EG35	EG18	EG17
	EG08	EG08	EG22	EG22	EG36	EG36	EG22	EG18
	EG17	EG17	EG16	EG04	EG39	EG39	EG16	EG22
	EG18	EG18	EG35	EG16	EG40	EG40	EG35	EG06
	EG22	EG22	EG36	EG35	EG03	EG03	EG36	EG07
	EG15	EG15	EG39	EG36	EG12	EG12	EG39	EG08
	EG20	EG20	EG40	EG39	EG19	EG19	EG40	EG16
	EG16	EG16	EG14	EG40	EG14	EG04	EG04	EG35
	EG35	EG35	EG29	EG14	EG29	EG14	EG14	EG36
	EG36	EG36	EG31	EG29	EG31	EG29	EG29	EG39
	EG39	EG39	EG20	EG31	EG20	EG31	EG31	EG40
	EG40	EG40	EG04	EG23	EG30	EG20	EG20	EG14
	EG14	EG14	EG30	EG06	EG32	EG06	EG06	EG29
	EG29	EG29	EG32	EG07	EG33	EG07	EG07	EG31
	EG31	EG31	EG33	EG08	EG34	EG08	EG08	EG23
	EG30	EG23	EG34	EG20	EG37	EG30	EG30	EG20
	EG32	EG30	EG37	EG30	EG38	EG32	EG32	EG30
	EG33	EG32	EG38	EG32	EG04	EG33	EG33	EG32
	EG34	EG33	EG23	EG33	EG06	EG34	EG34	EG33
	EG37	EG34	EG06	EG34	EG07	EG37	EG37	EG34
	EG38	EG37	EG07	EG37	EG08	EG38	EG38	EG37
	EG23	EG38	EG08	EG38	EG23	EG23	EG23	EG38
	EG09	EG09	EG09	EG09	EG09	EG09	EG09	EG09
	EG10	EG10	EG10	EG10	EG10	EG10	EG10	EG10
	EG11	EG11	EG11	EG11	EG11	EG11	EG11	EG11
	EG24	EG24	EG24	EG24	EG24	EG24	EG24	EG24
	EG25	EG25	EG25	EG25	EG25	EG25	EG25	EG25
	EG26	EG26	EG26	EG26	EG26	EG26	EG26	EG26
	EG27	EG27	EG27	EG27	EG27	EG27	EG27	EG27
	EG28	EG28	EG28	EG28	EG28	EG28	EG28	EG28

E-9. Financial Risk and Economics

The Criterion of Financial Risk and Economics was unique in the Evaluation and Screening study in that only one Evaluation Metric was used, the Levelized Cost of Electricity at Equilibrium (LCAE). The LCAE was the metric for another "challenge" criterion, Financial Risk and Economics, since it was considered that any alternative fuel cycle would likely face a challenge with respect to electricity production costs as compared to the current U.S. fuel cycle, especially for more complex fuel cycles. As discussed in Appendix A, the LCAE was not used as part of the process that identified the promising Evaluation Groups. The calculated LCAE estimates were associated with bins qualitatively comparing the expected electricity production costs with the current U.S. fuel cycle as listed in Table D-2.25.2. The resulting LCAE metric data was provided after the identification of the promising Evaluation Groups as additional information that could be considered by a decision-maker in evaluating potential fuel cycles for R&D and eventual deployment. More information on the LCAE is provided in Appendix C-9, and the detailed methodology for comparing LCAE results and the Metric Data are discussed in Appendix D-22.

E-10. Expert Opinions on the Evaluation Criteria

For each Criterion, the following are the expert opinions of one or more members of the EST who are subject-matter experts in the various fields represented by the Evaluation Criteria. The opinions are provided at the request of DOE for each Criterion and for the supporting Evaluation Metrics as reviewed in Sections E-1 to E-9 of this Appendix (stated for each criterion) and in Appendix D:

Nuclear Waste Management Criterion

- Factor of 10 or more reduction in the mass of SNF+HLW relative to the Basis of Comparison is a significant improvement: 28 of the 40 Evaluation Groups achieve at least this amount of reduction.
- The largest reduction in the activity of SNF+HLW at 100 years obtained over all the Evaluation Groups relative to the Basis of Comparison of 20% is not significant. However, the greater reduction in decay heat at 100 years (as derived from this metric), by a factor of 3 or more, is considered a significant improvement: 9 of the 40 Evaluation Groups achieve at least this amount of reduction.
- The reduction in the activity of SNF+HLW at 100,000 years obtained over all the Evaluation Groups (EGs) relative to the Basis of Comparison of 25% to 50% is not significant. However, the greater reduction in radiotoxicity at 100,000 years (as derived from this metric), which is the hazard posed by the wastes that requires their long-term isolation such as that provided by a geologic repository, by a factor of 10 or more, is considered a significant improvement: 7 of the 40 Evaluation Groups achieve at least this amount of reduction.
- Relative to the Basis of Comparison, a reduction by a factor of 100 or greater in the mass of DU+RU+RTh to be disposed is a significant improvement: 18 of the 40 Evaluation Groups achieve at least this amount of reduction.
- The largest reduction in the volume of LLW generated obtained over all the Evaluation Groups relative to the Basis of Comparison of up to 40% is not significant, so no Evaluation Groups achieve a significant reduction in LLW. However, the result that many of the Evaluation Groups contain fuel cycles (including those with recycle) that could be implemented without greatly increasing the volume of LLW generated is a significant conclusion.

Proliferation Risk Criterion

- For the Material Attractiveness - Normal Operating Conditions metric, all of the Evaluation Groups could be implemented using unattractive materials for normal operating conditions so that all of the groups had comparable material attractiveness and no promising options were identified.

Nuclear Material Security Risk Criterion

- For the Material Attractiveness - Normal Operating Conditions metric, all of the Evaluation Groups could be implemented using unattractive materials for normal operating conditions so that all of the groups had comparable material attractiveness and no promising options were identified.
- For the Activity of SNF+HLW (@10 years) per Energy Generated metric, all of the Evaluation Groups used highly radioactive materials and no promising options were identified.

Safety Criterion

- For the Challenges of Addressing Safety Hazards metric, most fuel cycles are equivalent in terms of the challenges of addressing the safety hazards that need to be addressed for implementation. Evaluation Groups involving externally-driven systems have identified safety challenges that have not been fully addressed through previous research program or applications and would require additional R&D to address. The potential for improvement of the safety of fuel cycles must be considered at the technology level based on technology choices and improvements and is the goal of on-going technology development programs.

- For the Safety of the Deployed System metric, fuel cycles in all Evaluation Groups could be deployed safely.

Environmental Impact Criterion

- The largest achieved decrease in land use over all the Evaluation Groups relative to the Basis of comparison of a factor of 3 is not significant improvement, so no Evaluation Groups achieve a significant reduction in the Land Use metric.
- Water use for virtually all Evaluation Groups is equivalent and most fuel cycles can be implemented without increasing water use as compared to the current U.S. fuel cycle. No Evaluation Group have lower water use requirements than the Basis of Comparison, so no Evaluation Groups achieve a significant reduction on the Water Use metric.
- The largest achieved decrease in CO_2 emissions over all the Evaluation Groups relative to the Basis of Comparison of a factor of 3 is not significant improvement, so no Evaluation Groups achieve a significant reduction in CO_2 emissions.
- All Evaluation Groups are equivalent in terms of the Radiation Exposure, so none are identified as providing a significant improvement on this metric.

Resource Utilization Criterion

- A factor of 10 or greater reduction in the Natural Uranium Required per Energy Generated relative to the Basis of Comparison is a significant improvement: 15 of the 40 Evaluation Groups achieve this significant reduction.
- While thorium can be used to displace uranium, either partially or completely depending on the fuel cycle, the overall use of fuel materials (uranium and/or thorium) remains about the same when a given fuel cycle is considered (if that fuel cycle is feasible with the use of both fuel materials).

Development and Deployment Risk Criterion

- As would be expected for the Development and Deployment Risk Criterion, those EGs that are based on existing, deployed technologies (such as once-through fuel cycles with thermal reactors and uranium fuel) rank highly with the Basis of Comparison (EG01) ranking the highest amount all EGs. The addition of new fuels, reactor types, and processing increases the Development and Deployment Risk and therefore, result in lower ranking for EGs that include those technologies. The EGs that introduce multiple new technologies, have the overall highest Development and Deployment Risk and therefore the lowest ranking.

Institutional Issues Criterion

- Fuel cycles that introduce new technologies result in the highest Institutional Issues, associated with less use of existing infrastructure, the lack of regulations and licensing familiarity and issues related to the development of markets that support the deployment of these fuel cycles.

Financial Risk and Economics Criterion

- Many of the Evaluation Groups identified as promising for other metrics may be expected to have electricity production costs that are comparable to, or close to, the current U.S. fuel cycle so that anticipated electricity production cost should not adversely impact decisions to pursue these promising options.