APPENDIX F

SCENARIO RESULTS

CONTENTS

FIGURES

TABLES

F. SCENARIO RESULTS

As described in Appendix A, to identify promising Evaluation Groups considering multiple criteria simultaneously, the Evaluation and Screening Team (EST) developed 11 scenarios, with each scenario representing a different perspective

F-1. Scenarios Considering Multiple Criteria

In each scenario, the EST calculated the benefit and the challenge of each Evaluation Group separately. As shown in Figure F-1.1, the EST combined four of the benefit criteria using criteria tradeoff factors to yield a calculated utility representing the overall benefit for each Evaluation Group (this parallels the approach used to combine multiple metrics into the utility for a single criterion discussed in Appendix E). The criteria of Proliferation Risk and Nuclear Material Security Risk were not included in this process since these two criteria were fundamentally different than the other four benefit criteria in that many of the considerations needed to inform on proliferation risk and nuclear material security risk were outside the scope of this study and were not amenable to a technical analysis of fuel cycles at the physics-based functional level. For the challenge criteria, the utility for the Development and Deployment Risk criterion (which contains all of the metrics also used to represent Institutional Issues) was used to represent the overall challenge of an evaluation group. The EST considered the Financial Risk and Economics criterion separately, as discussed in Appendix D, to provide insights on the promising options after determining the benefit and challenge for each Evaluation Group.

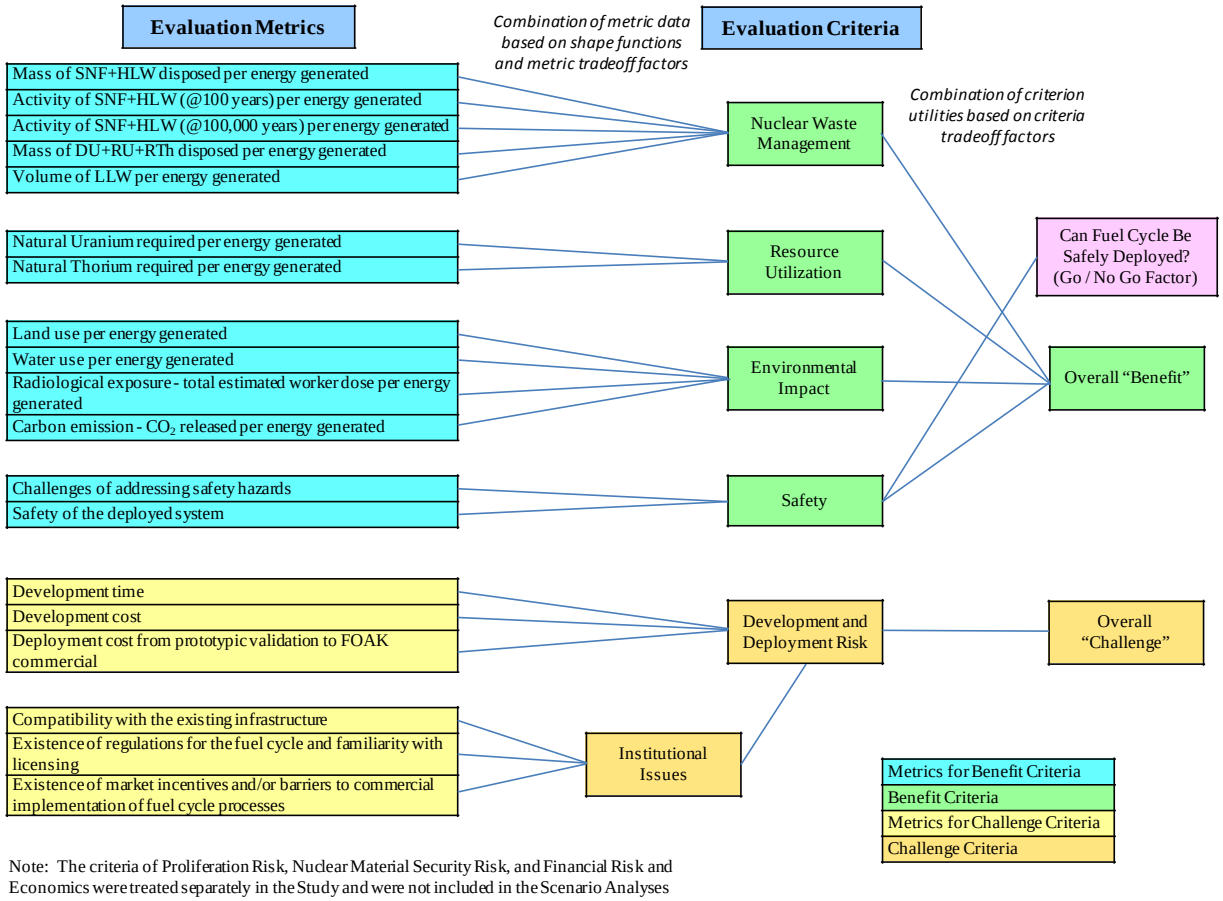


Figure F-1.1. Schematic Illustrating How Multiple Criteria were Combined to Yield Estimates of the Benefit and Challenge Associated with Each Evaluation Group.

In identifying "promising" fuel cycle options, both the metric data (the technical assessment of how an evaluation group performs against a metric) and judgments about the relative value of differences in performance are important. Appendix D summarizes the technical assessments, the metric data for each evaluation group. Appendix E introduces and summarizes the value judgments that were required to combine several metrics into a criterion-level evaluation through the use of shape functions and metric tradeoff factors. The final step, combining across multiple criteria, required one additional set of value judgments, in the form of *criteria tradeoff factors.* These factors represented the relative value or importance of changes in one criterion relative to changes in the others, as described in Appendix A-3.

To meet the charge in the Evaluation and Screening Charter that the evaluation and screening "will explore the impacts of different criteria weighting factors that reflect the range of possible policy guidance and illustrate the effects of specific policy choices," the EST defined a set of "scenarios," through the use of alternative criteria tradeoff factors reflecting different possible judgments about what "matters" (and how much it matters) in determining the promise of an alternative fuel cycle.

These scenarios were grouped into three categories:

- One scenario where the importance of change in each of four Benefit Criteria (Nuclear Waste Management, Resource Utilization, Environmental Impact, and Safety) was equal
- Four scenarios which emphasize changes in a single Criterion with respect to the three other Benefit Criteria
- Six scenarios representing other perspectives, as reflected by the relative importance of change in subsets of these four Benefit Criteria.

Content and Structure of Appendix F:

This Appendix describes the results of the analysis of scenarios considering multiple Evaluation Criteria simultaneously. Section F-1.1 describes the specific scenarios that were evaluated. Section F-1.2 describes the analyses that were conducted and previews how the scenario results are presented in the subsequent Sections. Section F-2 describes the results for each Scenario, identifying the promising Evaluation Groups for the scenario and the R&D needs that would help enable the technologies for those promising Evaluation Groups. Section F-3 summarizes the results of the scenario analyses and describes the results of a scenario-level sensitivity analysis that considers an even wider range of possible criteria tradeoff factors than the 11 scenarios evaluated in detail, resulting in the sets of promising Evaluation Groups for the study.

F-1.1. Scenario Definitions

The eleven scenarios defined and analyzed for this study for the four Benefit Criteria (Nuclear Waste Management, Resource Utilization, Environmental Impact, and Safety) are as follows:

- Scenario 1 – changes in the four Benefit Criteria are of equal importance, reflected by each Criterion being assigned equal tradeoff factors as their utilities are combined, indicating the potential for improvement in any of the Criteria based on the choice of fuel cycle.
- Scenario 2 - explore the importance of differences between Evaluation Groups on the Nuclear Waste Management criterion versus a balance of the three other benefit criteria.
- Scenario 3 - explore the importance of differences between Evaluation Groups on the Resource Utilization criterion versus a balance of the three other benefit criteria.
- Scenario 4 - explore the importance of differences between Evaluation Groups on the Environmental Impact criterion versus a balance of the three other benefit criteria.

- Scenario 5 - explore the importance of differences between Evaluation Groups on the Safety criterion versus a balance of the three other benefit criteria.

For each of the Scenarios 2 through 5, the criteria tradeoff factor for the emphasized Criterion was set at 0.7, with the other benefit criteria at 0.1 each. A sensitivity analysis was conducted where the criteria tradeoff factor for the emphasized Criterion was varied from 1 to 0.3 (essentially the same weights as Scenario 1), in increments of 0.1. These sensitivity studies identified any changes to the order of the Evaluation Groups from highest to lowest utility as the tradeoff factor for the emphasized Criterion was decreased, informing on the contribution of that single Criterion to the overall results.

Six other scenarios were defined, each exploring an emphasis on a sub-set of the four Benefit Criteria, each defined to reflect one of a variety of perspectives. These scenarios are:

- Scenario 6 - emphasize the importance of differences between Evaluation Groups on the Nuclear Waste Management, Resource Utilization, and Environmental Impact criteria– to focus on the direct physical impacts of producing nuclear power and the potential to reduce the impacts by choice of fuel cycle.
- Scenario 7 - de-emphasize the importance of differences between Evaluation Groups on the Environmental Impact criterion, focusing instead on the potential for improvement in Nuclear Waste Management, Resource Utilization, and Safety Criteria based on choice of fuel cycle.
- Scenario 8 - de-emphasize the importance of differences between Evaluation Groups on the Resource Utilization criterion– to explore the potential impact of expanded fuel resource availability (such as uranium from seawater) and its effect on the relative benefits of fuel cycles. This scenario also provides insight on whether Resource Utilization as a separate criterion adds a different perspective to the results.
- Scenario 9 - de-emphasize the importance of differences between Evaluation Groups on the Nuclear Waste Management criterion – to explore, in combination with Scenarios 1, 7 and 8, any potential overlap between the Nuclear Waste Management and the Resource Utilization criteria and the potential impact on the choice of fuel cycle.
- Scenario 10 - emphasize the importance of differences between Evaluation Groups on the Nuclear Waste Management and Resource Utilization criteria – to focus on long-term and large-scale sustainability issues and the potential impact of the choice of fuel cycle.
- Scenario 11 - emphasize the importance of differences between Evaluation Groups on the Nuclear Waste Management and Safety criteria– to explore a perspective reflecting the most prominent current concerns and the potential impact of the choice of fuel cycle.

Table F-1.1.1 shows the criteria tradeoff factors used for each criterion in each of the Scenarios explored. The criteria tradeoff factors represent the relative importance of changes in each criterion, where "changes" are defined relative to the full range of the bin structure for all Evaluation Metrics for that Criterion.

Table F-1.1.1. Criteria Tradeoff Factors Used for Each of the Eleven Scenarios.

Scenario	Nuclear Waste Management Criterion	Resource Utilization Criterion	Environmental Impact Criterion	Safety (Safety Challenge Metric only)
1. Equal Criteria Tradeoff Factors	0.25	0.25	0.25	0.25
2. Emphasize changes in the Nuclear Waste Management Criterion	0.7	0.1	0.1	0.1
3. Emphasize changes in the Resource Utilization Criterion	0.1	0.7	0.1	0.1
4. Emphasize changes in the Environmental Impact Criterion	0.1	0.1	0.7	0.1
5. Emphasize changes in the Safety Criterion	0.1	0.1	0.1	0.7
6. Reduce physical impacts of producing nuclear power(1)	0.33	0.33	0.33	
7. Nuclear Waste Management, Resource Utilization, and Safety Criteria	0.33	0.33		0.33
8. Unlimited natural fuel resources	0.33		0.33	0.33
9. Resource utilization, Environmental Impact, and Safety Criteria		0.33	0.33	0.33
10. Nuclear Waste Management and Resource Utilization Criteria only	0.5	0.5		
11. Nuclear Waste Management and Safety Criteria only	0.5			0.5

(1) Criteria tradeoff factors sum to 1. For this and all other scenarios including three criteria, the tradeoff factors are displayed as 0.33 but should be understood to represent 1/3.

F-1.2. Scenario Analysis and Results Descriptions

Several types of analyses were conducted for each scenario.

Basis for analyses

The basis for all of the analyses was the benefit and challenge calculations. A utility representing benefit and a utility representing challenge was calculated for each Evaluation Group, and the results were plotted on a Benefit vs. Challenge graph (see example in Figure F-1.2.1). The utility representing the benefit of each evaluation group was calculated using the benefit criteria included in the scenario and the shape functions and metric tradeoff factors for the initial Criterion level analyses described in Appendix E. This utility is plotted on the y-axis. The x-axis is the challenge for each evaluation group, where challenge is represented by the utility for the Development and Deployment Risk Criterion, again using the initial shape functions and metric tradeoff factors identified in Appendix E. (The metrics for the Institutional Issues criterion were also used for the Development and Deployment Risk criterion, so the x-axis can be viewed as representing both of these challenge criteria.) 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, shown in red). Evaluation Groups that are higher on the y-axis have higher benefit than those lower on the graph. Similarly, Evaluation Groups that are farther to the left on the x-axis pose increasingly greater challenges to develop and implement.

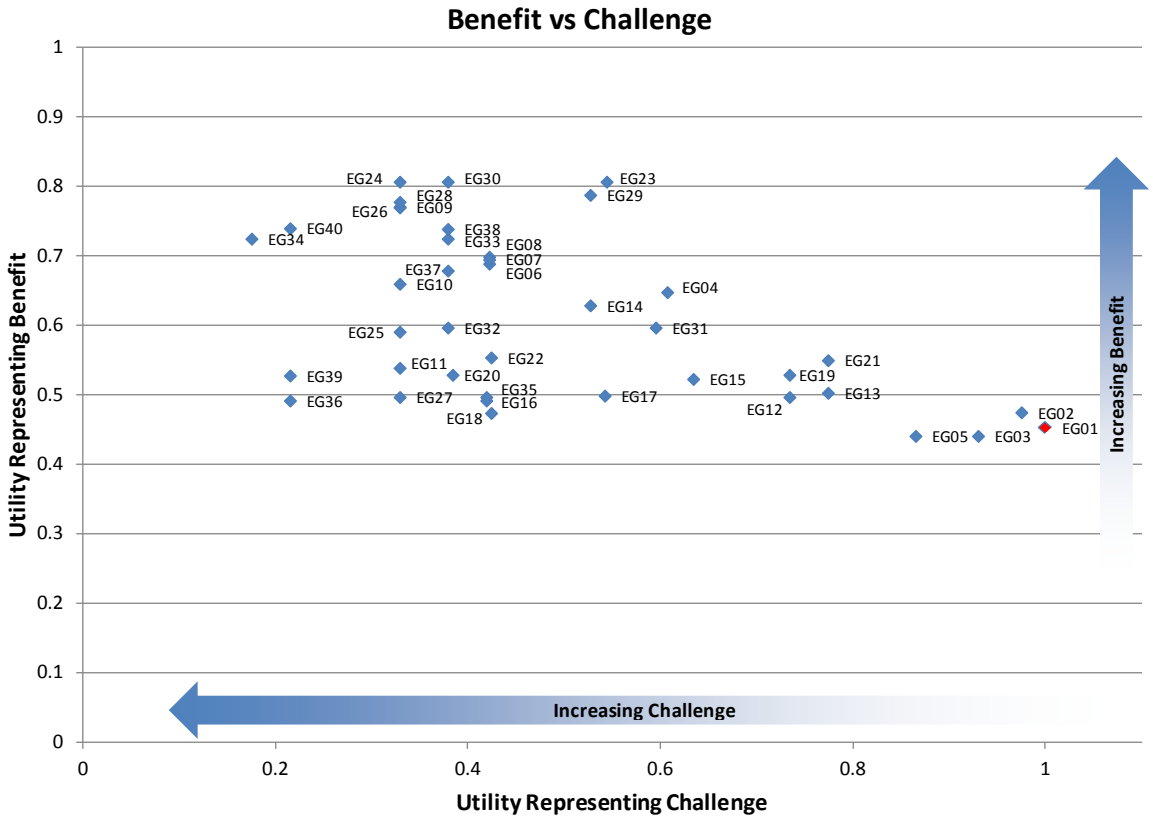


Figure F-1.2.1. Example of a Benefit versus Challenge Plot.

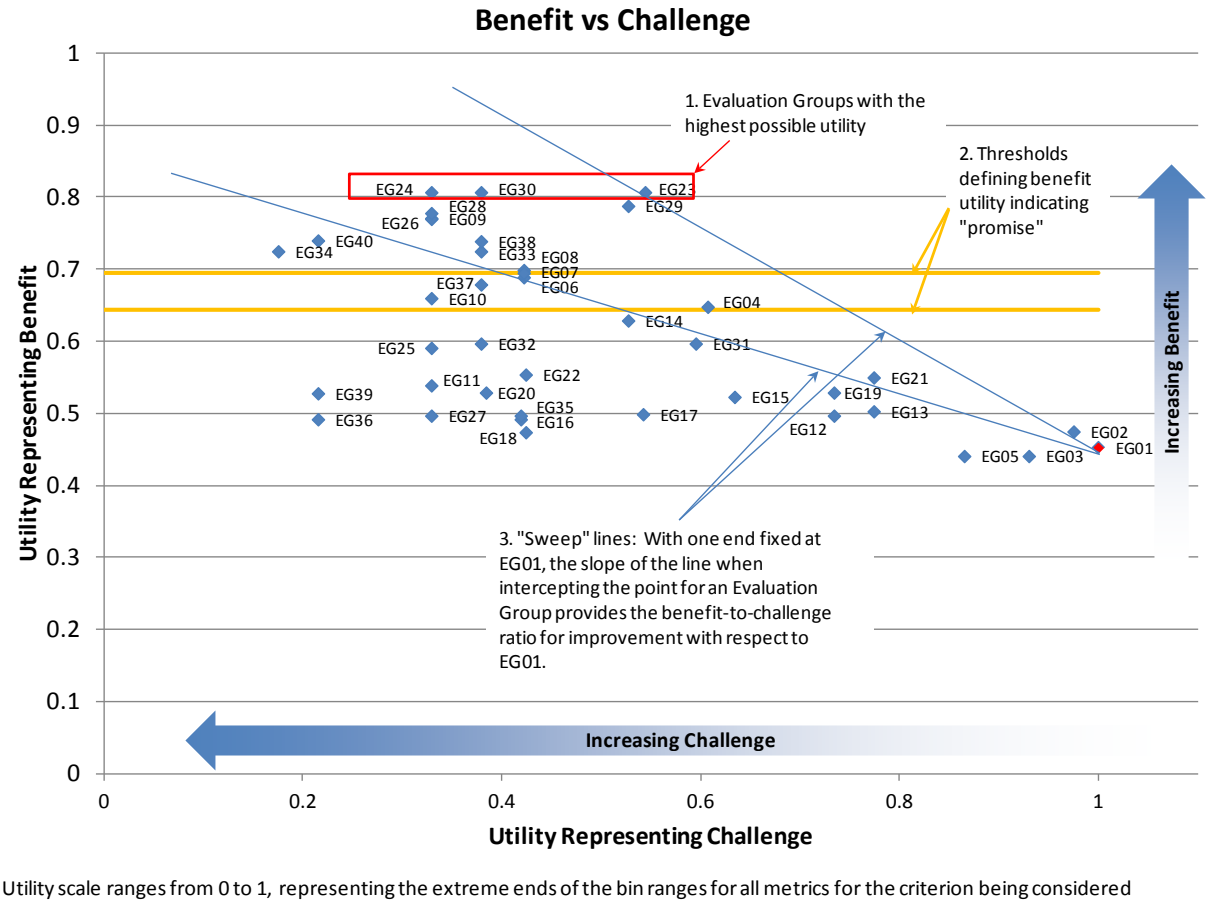
There are numerous ways in which this benefit-versus-challenge graph can be interpreted, including:

(1) A focus on benefits: either moving "down" from the top of the plot to identify the best performing Evaluation Groups, or moving "up" from the Basis of Comparison to identify those that offer "a little" to "a lot" of incremental benefit.
(2) A focus on challenge: moving to the left from the Basis of Comparison to identify Evaluation Groups that may be easier to develop and implement than others while still offering benefits over the Basis of Comparison; as one moves further to the left evaluation groups with higher development and deployment challenges can be identified.
(3) Consideration of both benefit and challenge, to identify Evaluation Groups that offer the most benefit for the least challenge.

Because the emphasis in this evaluation and screening is to identify fuel cycles that offer the potential for "substantial improvement" over the Basis of Comparison, the analyses of each scenario focused more on the incremental benefit of the Evaluation Groups (interpretation 1), while also considering the incremental benefit to incremental challenge ratio (interpretation 3) for those Evaluation Groups identified as promising.

Analyses Focused on Benefits

For each scenario, the EST identified the Evaluation Groups that have the highest benefit, as on Figure F-1.2.2.



Utility scale ranges from 0 to 1, representing the extreme ends of the bin ranges for all metrics for the criterion being considered

Figure F-1.2.2. Examples of Several Types of Analyses Conducted to Identify Promising Sets of Evaluation Groups.

This identifies those groups that provide the most benefit for that scenario, under the specific set of shape functions and metric tradeoff factors used for that set of calculations (sensitivity to different shape functions and metric tradeoff factors is discussed below). For each scenario, "potentially promising" Evaluation Groups may also be identified, based on the definition and use of utility "threshold(s)" values similar to those defined at the Criterion level, as discussed in Appendix E. The orange line (labeled 2) in Figure F-1.2.2 illustrates an example threshold: all Evaluation Groups above this line would be identified as promising groups for a decision-maker who determines that the line represents sufficient improvement. For some scenarios, no Evaluation Groups are identified as potentially promising, just as for some Criteria no promising options were identified. For other scenarios, multiple thresholds were considered, identifying several such sets of potentially promising Evaluation Groups.

When considering the benefit utility of each Evaluation Group, an obvious and critical question arises: How *much* improvement over the Basis of Comparison is "significant?" As was the case at the metric level and the criterion level, the answer to that question is a matter of judgment.

At the **metric level**, the EST addressed this issue by presenting results as a set of conditional statements, identifying Evaluation Groups by metric bin for all bins better than that of Basis of Comparison, and postulating if a given level of improvement for each metric bin were considered significant, then the corresponding set of Evaluation Groups meeting or exceeding that level of improvement is listed as promising (See Appendix D).

At the **criterion level**, the EST addressed this question by defining zero, one, or two "threshold" utility values to identify a level of benefit that might be considered a "significant" improvement for that criterion. Thresholds at the criterion level were defined based on explicit consideration of the amount of improvement over the Basis of Comparison on the evaluation metrics for that criterion, and the calculated criteria utility for that set of metric data using one set of shape functions and metric tradeoff factors. This led to a similar conditional identification of promising groups, where each threshold was identified as a utility that could represent a "significant" improvement over the Basis of Comparison, and then all Evaluation Groups exceeding each threshold(s) were identified (See Appendix E). Different decision-makers could define different threshold values.

At the **scenario level**, the threshold approach is used again, with the scenario thresholds calculated from the criterion-level thresholds. For three of the benefit criteria, at least one threshold for identifying promising groups was defined (Nuclear Waste Management, Environmental Impact, and Resource Utilization). For the Safety criterion, no Evaluation Groups out-performed the Basis of Comparison, so no thresholds were defined. Thresholds for defining potentially promising sets at the scenario level were determined by translating the criterion-level thresholds to combined utility thresholds using the criteria tradeoff factors for the scenario. For the Safety criterion threshold greater than the utility of EG01 was used for purposes of calculating a scenario-level threshold. For example, for Scenario 1, four benefit criteria are included, and all have equal tradeoff factors. Thus the thresholds considered for Scenario 1 were defined as an equally-weighted sum of the thresholds for each of the criteria, calculated as shown in Table F-1.2.1.

Table F-1.2.1. Example Calculation of Scenario 1 Benefit Thresholds from the Thresholds for the Included Criteria.

	Nuclear Waste Management Criterion	Resource Utilization Criterion	Environmental Impact Criterion	Safety Criterion	Benefit utility	**Incremental utility over EG01**
Threshold 1	0.842	0.608	0.828	0.5	0.694	**0.24**
Threshold 2	0.638				0.643	**0.19**
EG01	0.304	0.200	0.810	0.5	0.453	
Tradeoff factors	0.25	0.25	0.25	0.25		

Analyses Considering both Benefit and Challenge

For each scenario, a second type of analysis was conducted that considers both the increased benefit and the challenge of achieving that greater benefit. For each of the potentially promising sets of Evaluation Groups identified by the threshold values, Evaluation Groups in that set were ranked based on the ratio of incremental benefit to incremental challenge. "Incremental" was 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 benefit versus challenge graph and that line is "swept" to the left while remaining anchored at EG01. This is shown by the lines (labeled 3) on Figure F-1.2.2. The first Evaluation Group intercepted by that line has the highest ratio of incremental promise to incremental challenge (EG23 in the example shown). 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 (such as EG02 in the example).

In addition to producing this ranking by incremental benefit to incremental challenge, the EST explored several other approaches for ranking and comparing Evaluation Groups based on consideration of both benefit and challenge, and found that they did not lead to new or unique insights beyond those obtained by the main analyses presented in the remainder of this Appendix. For example, an additional threshold was considered, defined by a specific ratio of benefit-to-challenge, and Evaluation Groups that were above both the benefit threshold and the benefit-to-challenge ratio were identified. Conceptually, this benefit-to-challenge threshold represents a "desired" or "acceptable" balance between benefit and challenge, and Evaluation Groups can be ranked by how much they exceed this minimum acceptable balance. In practice, these analyses yielded results very similar to those found using the promise-challenge "sweep" approach.

Sensitivity Analyses: Consideration of Multiple Perspectives

The calculations and results described above are by necessity the detailed results for one set of shape functions and metric tradeoff factors, and one set of criteria tradeoff factors. As discussed in Appendix E, the calculated utility values for an Evaluation Group vary when alternative shape functions and metric tradeoff factors are used. Each combination of shape functions and metric tradeoff factors represents a different set of value judgments (or perspectives) that a decision-maker might hold; thus there is no "right" set of judgments. When all shape functions and metric tradeoff factors that were retained to illustrate sensitivity at the criterion level are considered in all combinations, there are over 25,000 perspectives that could be considered for a scenario that includes all the criteria. Figure F-1.2.3 illustrates the range of utility scores on the benefit criteria and the range of utility scores on the challenge criteria for each evaluation group for one scenario. While these ranges appear very broad, there is a strong correlation between the evaluation groups, so that if the utility of one Evaluation Group is "low" from a benefit perspective for a particular set of shape functions, metric tradeoff factors, and criteria tradeoff factors, it is very likely that the utility of most other Evaluation Groups will also be low.

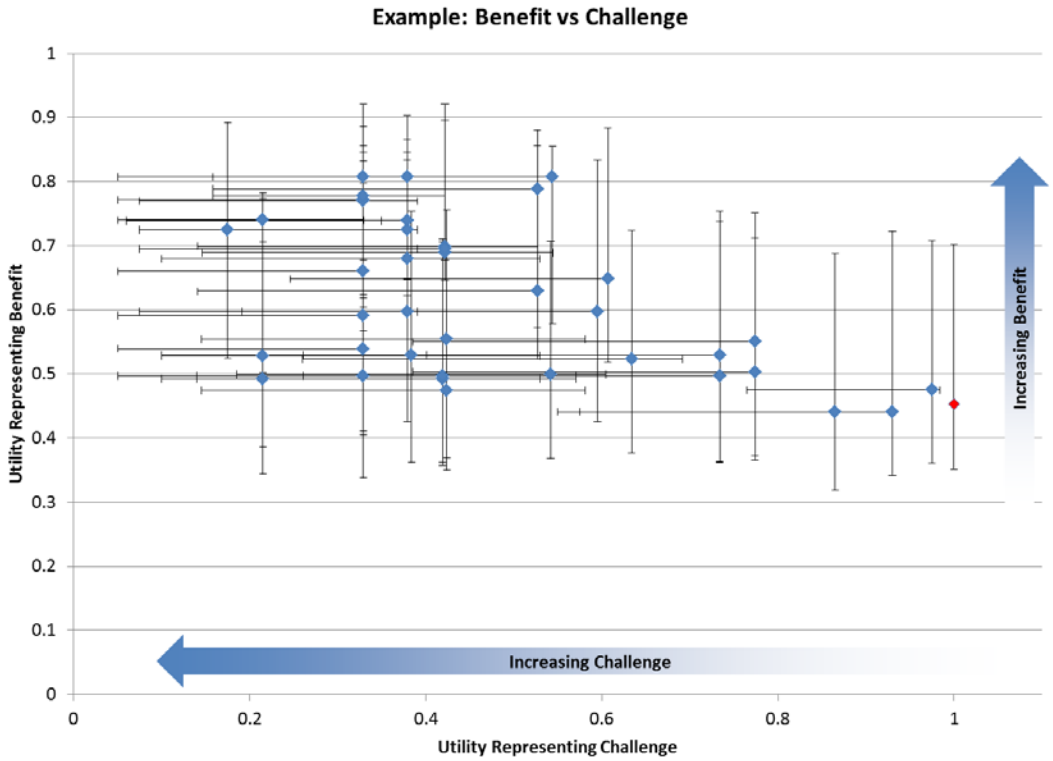


Figure F-1.2.3. Example Showing the Range of Performance for Each Evaluation Group in Terms of the Combined Benefit and Challenge, for One Scenario While Considering All Combinations of Shape Functions and Metric Tradeoff Factors.

To examine the impact of these many perspectives on the overall results at the scenario level, simulation studies were conducted. In these simulations, one shape function for each evaluation metric was sampled at random from the set considered, one set of metric tradeoff factors for each criterion was sampled at random from the set defined for that criterion, and the resulting benefit utility and challenge utility for each Evaluation Group was calculated using the criteria tradeoff factors defined for the scenario being evaluated. All shape functions and metric tradeoff factor sets were sampled independently. 10,000 iterations of the simulation were run. To test the sufficiency of the number of iterations, several tests were run with up to 1 million iterations. Only small differences were seen between the results with 10,000 iterations and the results with 1 million iterations, and those differences occurred only for evaluation groups that rarely met the thresholds defined as sufficient to be considered promising. For purposes of this evaluation and screening, 10,000 iterations appeared to be sufficient to identify both the robust Evaluation Groups and any groups that are promising under a subset of perspectives.

In these sensitivity studies, samples were generated from the set of all possible shape functions and metric tradeoff factors for the included criteria, , the benefit and challenge utility values were calculated, and the analyses described above were conducted to determine which Evaluation Groups lie in a potentially promising set, and what the incremental benefit to incremental challenge ratio was for each of those promising Evaluation Groups. From these results, the EST looked at two questions: how often is each Evaluation Group in a potentially promising set, and what is the average (and range) of the ratio of incremental benefit to incremental cost for each Evaluation Group? The answers to these questions help identify the promising Evaluations Groups that are robust to different perspectives – those that are in a potentially promising set under most perspectives, and help to identify Evaluation Groups that may be considered promising under only a few perspectives. For the latter cases, the perspectives that lead to an Evaluation Group being considered promising are identified and discussed.

Applying utility thresholds under different shape functions and metric tradeoff factors

As discussed above, the choice of a threshold is inherently a value judgment, and several different methods could be used to define thresholds. The EST chose to define thresholds by considering the metric data directly and then calculating a utility for that set of metric data using one of the perspectives articulated for the criterion (one set of shape functions and metric tradeoff factors). While this approach has the benefit of making one clear tie to metric data, it carries a complication in that the value judgments required to set the threshold are be very similar to the value judgments that are required to define the different shape functions and metric tradeoff factors.

The threshold can be interpreted and implemented in several ways. The approach that is closest to what would be done if this evaluation and screening were being conducted for a single, well-defined decision-maker would be to work with that decision-maker to establish a threshold that corresponds to his perspective and is aligned with the shape functions and tradeoff factors he provided. In the context of this evaluation and screening, that would mean establishing unique but compatible thresholds for every combination of shape functions and metric tradeoff factors. That approach is impractical for two reasons: first because there are simply too many perspectives being considered, and second, identifying thresholds for each perspective that are comparable – so that an Evaluation Group that exceeds the threshold for one perspective is "as beneficial" to a decision maker holding that perspective as is an Evaluation Group that exceeds a different threshold is for a different decision-maker – is not feasible in the abstract.

Instead, an alternative interpretation was used: the incremental utility of the threshold(s) over the utility of the Basis of Comparison was calculated using the initial set of shape functions, metric and criteria tradeoff factors (e.g., +0.19 over EG01 for Threshold 2 shown in Table F-1.2.1) and that incremental value was treated as the threshold(s) for all perspectives, creating a single set of incremental thresholds regardless of perspective (the incremental thresholds are dependent on the perspective). As a consequence, this approach has the benefit of simplifying the analyses since unique thresholds are not

defined for each unique perspective. In practice, this approach can lead to results where under some perspectives no Evaluation Groups meet the threshold values. In particular, if the initial perspective established a very high threshold with respect to a metric or criterion that was strongly emphasized, under alternative perspectives it may not be numerically possible for any Evaluation Group to achieve the same level of incremental benefit. However, if a threshold value specific to each perspective had been determined, potentially promising Evaluation Groups may exist that would not be identified with this approach. Overall, this approach takes advantage of the judgments already encoded in the shape functions and metric tradeoff factors, and focuses on the improvement over the Basis of Comparison, per the Charter for the study.

With this understanding, this threshold approach as implemented here is useful in identifying the degree of robustness of promising Evaluation Groups for the breadth of perspectives represented by the different combinations of shape functions and tradeoff factors and provides a relative indication for all Evaluation Groups for meeting or exceeding these increment thresholds, recognizing that this approach could underestimate the robustness of the results. The final set of scenario-level sensitivity analyses in Section F.2 considers incremental benefit values directly, reducing the influence of the threshold value on the study conclusions.

Figure F-1.2.4 illustrates how these sensitivity results are presented in the subsections below. For a given threshold utility, the graph shows the percentage of simulation runs under which the Evaluation Group was in the promising set (the blue bars and the left axis), and the ratio of incremental promise to incremental challenge for all cases where the Evaluation Group is in the promising set (the grey markers and red lines, with values shown on the right axis). The example below includes “error bars” representing the range of this ratio across the full set of simulations. The ratio of incremental benefit to incremental challenge varies a great deal based on the shape functions and metric tradeoff factors considered. Similar to the discussion of Figure F-1.2.3, although the ranges of incremental benefit to incremental cost for each Evaluation Group may appear fairly broad, there is sufficient correlation between the Evaluation Groups so that if the ratio for one Evaluation group is “low” in its range, it is likely to be “low” for the other Evaluation Groups as well. The average ratio (represented by the marker) was chosen as a summary measure of the incremental benefit-challenge ratio. In the sensitivity analysis figures for each subsection below, only this average value is presented. Note that in this particular example, there are no Evaluation Groups that are consistently in a potentially promising set – this is due to the approach of using a relatively high threshold value determined from one set of shape functions, metric tradeoff factors, and criteria tradeoff factors, such that under some perspectives and the corresponding sets of shape functions, metric tradeoff factors, and criteria tradeoff factors, the high threshold cannot be achieved by any Evaluation Group. The sensitivity analyses identify those Evaluation Groups that are most robust for any given threshold for a multitude of shape functions and tradeoff factors.

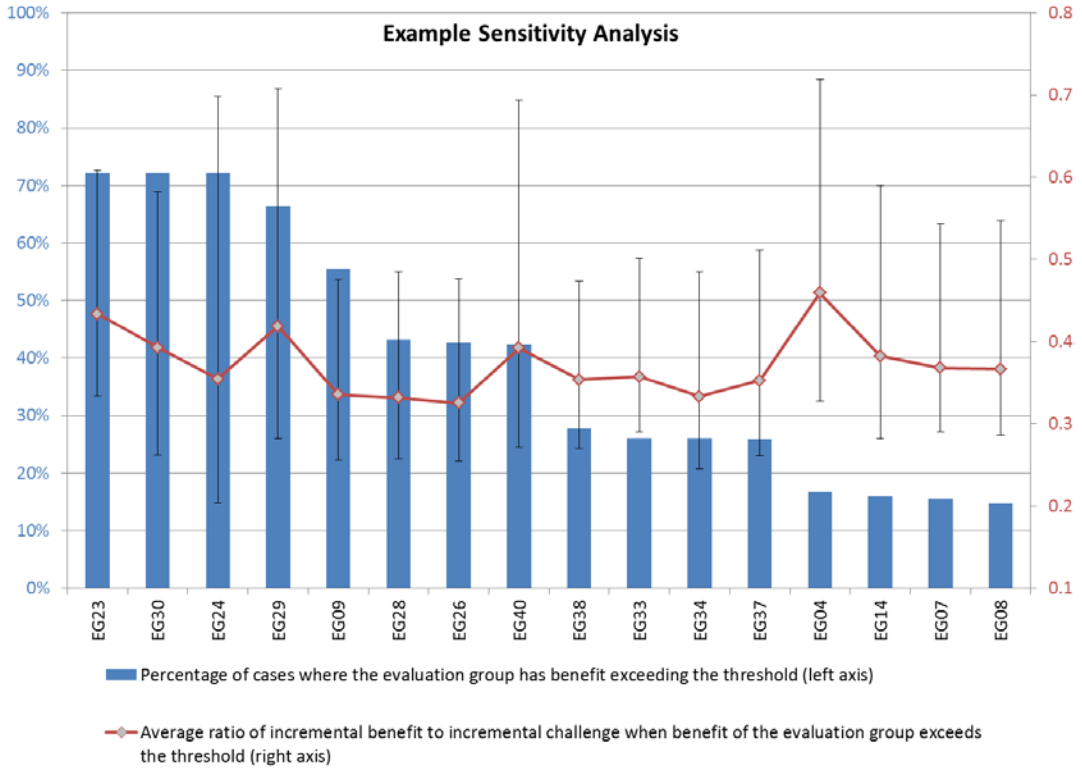


Figure F-1.2.4. Example Illustrating Sensitivity Results: Frequency with which Each Evaluation Group is in the Promising Set, and the Ratio of Incremental Benefit to Incremental Challenge for Those Evaluation Groups.

F-2. Results for Individual Scenarios

This section presents the results for each Scenario.

F-2.1 Scenario 1 – Equal Criteria Tradeoff Factors

Definition of the Scenario: This scenario considered changes in the four benefit criteria of Nuclear Waste Management, Environmental Impact, Safety, and Resource Utilization to be of equal importance, reflected by the utility for each criterion having equal tradeoff factors as their utilities are combined, indicating the potential for improvement in any of the Criteria based on the choice of fuel cycle.

Criteria tradeoff factors: Each of the four included benefit criteria was assigned a tradeoff factor of 0.25.

Results

The benefit and challenge results for this scenario are presented in Figure F-2.1.1.

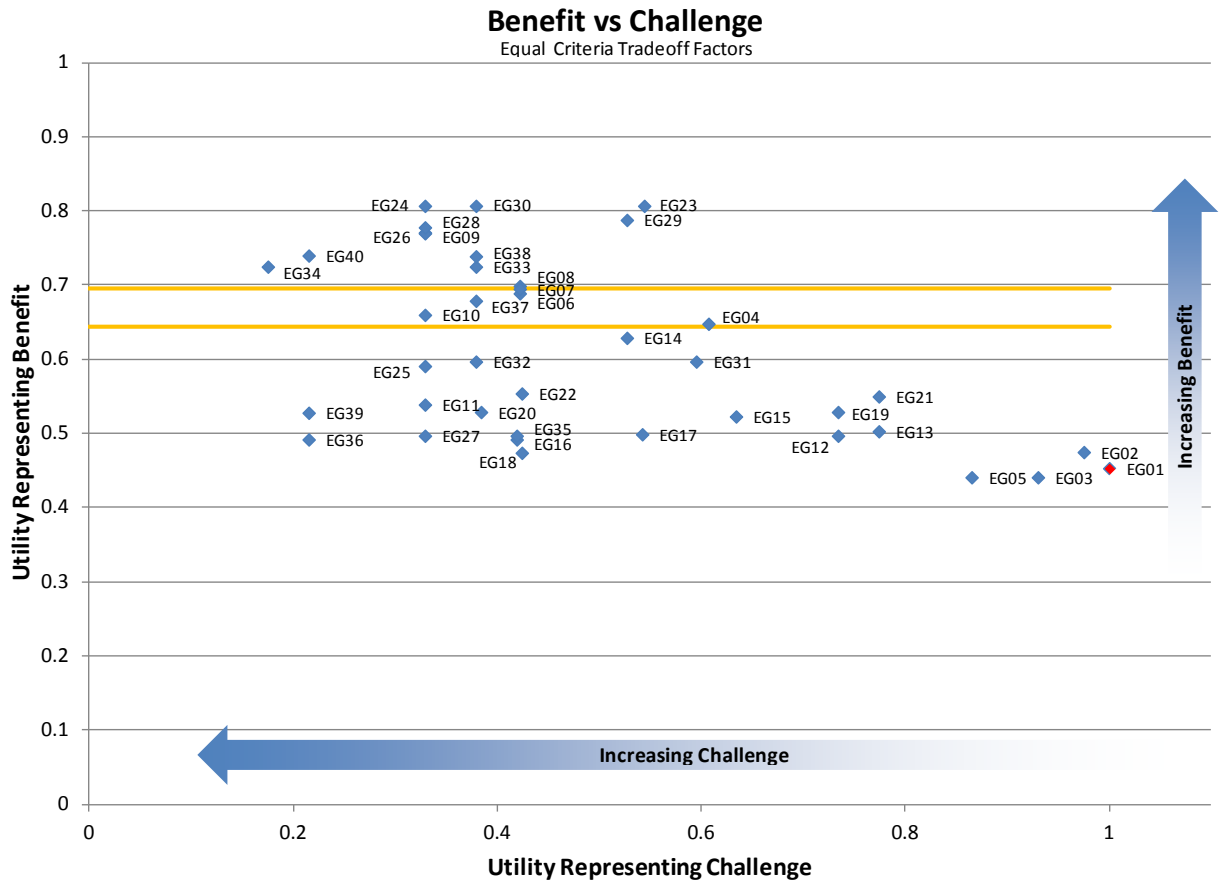


Figure F-2.1.1. Benefit versus Challenge Results for Scenario 1, Equal Criteria Tradeoff Factors, for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups considering benefit alone

The list of potentially promising Evaluation Groups that corresponds to benefit alone is shown in Table F-2.1.1. In addition to considering the Evaluation Groups with highest possible utility, two utility thresholds were defined to identify potentially promising sets of Evaluation Groups, as illustrated in Figure F-2.1.1 and described in the table. For this scenario, the two thresholds were defined, based on the two thresholds defined in Appendix E for the Nuclear Waste Management criterion and the single threshold defined for each of the other benefit criteria. Threshold 1 was defined by a benefit utility of at least 0.69 (at least 0.24 greater than that of the Basis of Comparison), and Threshold 2 was defined by a benefit utility of at least 0.65 (at least 0.19 greater than that of the Basis of Comparison).

Three Evaluation Groups have the highest utility value for this scenario: continuous recycle of U/Pu and U/TRU in fast critical reactors without enrichment and continuous recycle of U/TRU with both fast and thermal critical reactors without enrichment (EG23, EG24, and EG30).

Threshold 1 identifies promising Evaluation Groups that include additional continuous recycle options, and once-through and limited recycle options as well. EG07 and EG08 are once-through systems with very high burnup using externally driven systems (EDS). EG09 is limited recycle of U with very high burnup fuels (in a fast critical reactor without enrichment). The expanded promising set as determined by Threshold 2 includes additional once- through and limited recycle options, such as EG06 (once through Th fuel using thermal EDS), EG14 (limited recycle of U/Pu with both fast and thermal critical reactors without enrichment), and EG04 (once-through U to very high burnup in fast critical reactor without enrichment). Seven of the Evaluation Groups included in this promising set use thorium feeds (EG06,

EG08, EG10, EG26, EG28, EG38, and EG40), and only one (EG37) uses enriched uranium (but a small amount).

Table F-2.1.1. List of Promising Evaluation Groups by Benefit, Scenario 1.

Threshold Type	Evaluation Groups Within Threshold
Highest Possible Benefit Utility (0.81)	EG23, EG24, EG30
Promising groups based on highest utility score	
Threshold 1 (Benefit utility = 0.69; 0.24 higher than EG01)	EG07, EG08, EG09, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG38, EG40
Promising groups based on upper thresholds established for individual Criteria and proportioned by the criteria tradeoff factors defined for the Scenario	
Threshold 2 (Benefit utility = 0.64; 0.19 higher than EG01)	EG04, EG06, EG07, EG08, EG09, EG10, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG37, EG38, EG40
Promising groups based on lower thresholds established for individual Criteria (as applicable) and proportioned by the criteria tradeoff factors defined for the Scenario	
Color code	Once through / Limited recycle / Continuous recycle

Rankings considering both benefit and challenge

When accounting for the challenge of achieving the potential benefit, ordered lists by the ratio of incremental benefit to incremental challenge relative to the Basis of Comparison (EG01) can offer additional insights. Table F-2.1.2 shows the ranking of the Evaluation Groups within each of the promising sets identified above based on this ratio The numeric values show the incremental benefit utility of the Evaluation Group (over the benefit utility of the Basis of Comparison) divided by the incremental challenge utility (over the challenge utility of the Basis of Comparison). As one can see from comparing columns in the table, when both benefit and challenge are considered, several continuous recycle Evaluation Groups rank highly, including all three Evaluation Groups with the highest benefit utility for this scenario: continuous recycle of U/Pu and U/TRU in fast critical reactors without enrichment (EG23 and EG24) and continuous recycle of U/TRU with both fast and thermal critical reactors without enrichment (EG30). Continuous recycle of U/Pu with both fast and thermal critical reactors without enrichment (EG29) also ranks highly, and considering the extended promising set with the lower threshold, EG04 (once-through U to very high burnup in fast critical reactor without enrichment) ranks highly.

Sensitivity analyses

Because this scenario includes consideration of four benefit criteria as well as the challenge criteria, it has the largest set of different perspectives that could be considered of any scenario. Following the approach described in Section F-1.2, a sensitivity analysis was done across all combinations of shape functions and metric tradeoff factors considered in the individual criterion analyses, for all included criteria simultaneously. The criterion-level results were combined with equal tradeoff factors as defined by this scenario.

Table F-2.1.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio* for Different Utility Thresholds, Scenario 1.

Highest possible benefit utility ordered by incremental benefit/challenge ratio		Threshold 1 groups ordered by incremental benefit/ challenge ratio		Threshold 2 groups ordered by incremental benefit/ challenge ratio	
EG23	0.78	EG23	0.78	EG23	0.78
EG30	0.57	EG29	0.71	EG29	0.71
EG24	0.53	EG30	0.57	EG30	0.57
		EG24	0.53	EG24	0.53
		EG28	0.48	EG04	0.50
		EG09	0.47	EG28	0.48
		EG26	0.47	EG09	0.47
		EG38	0.46	EG26	0.47
		EG33	0.44	EG38	0.46
		EG07	0.43	EG33	0.44
		EG08	0.42	EG07	0.43
		EG40	0.37	EG08	0.42
		EG34	0.33	EG06	0.41
				EG40	0.37
				EG37	0.36
				EG34	0.33
				EG10	0.31

* "Incremental" is defined by the difference in performance, on the utility scale representing benefit, and on the utility scale representing challenge, between an Evaluation Group and Basis of Comparison (EG01).

Figures F-2.1.2(a-b) illustrate the sensitivity analysis results considering each of the two thresholds defined above: the percentage of simulation runs under which the Evaluation Group was in that set (the blue bars and the left axis), and the average ratio of incremental promise to incremental challenge for all cases where the Evaluation Groups is in the promising set (the red markers and the right axis). Together, these results highlight seven Evaluation Groups that are robust to the various perspectives, and provide an ordering of these Evaluation Groups that takes into account both the benefit and the challenge of reaching that benefit: EG23, EG30, EG24, EG29, EG09, EG28, EG26, and EG40. These eight Evaluation Groups are in the promising set defined by the second threshold for over 70% of the different perspectives considered, and are in the promising set defined by the higher threshold more often than any other Evaluation Group.

As discussed in Section F-1.2, the thresholds established for this scenario are implemented using same incremental benefit above that of the Basis of Comparison (EG01) as that for the initial set of shape functions and metric tradeoff factors. The results indicate that for some tradeoff factors and shape functions, no promising options are identified. However, the results demonstrate the level of robustness of the promising options, by indicating those that do meet the threshold(s) most often across the multitude of tradeoff factors and shape functions considered.

The sensitivity analysis results also identify several other Evaluation Groups that are not robust performers but may warrant further consideration under specific subsets of decision-maker perspectives:

- EG04 exceeds the lower promise threshold in roughly half of the cases considered, and when it does it offers relatively high incremental promise for lesser challenge than several of the "robust" evaluation groups.
- EG14 is in the promising set in about 35% of cases when the lower threshold is considered, and when it is in that set it also offers relatively high incremental benefit for lesser challenge than several of the "robust" evaluation groups. EG14 performs well (and is in the promising set) primarily when the metric tradeoff factors for Nuclear Waste Management that place more emphasis on DU, RU, and RTh are used.
- Although EG06, EG07, and EG08 are in the promising set identified by the second threshold in Table F2.1.1, when other perspectives are considered in the sensitivity analysis, they exceed this threshold under fewer than 50% of those perspectives.

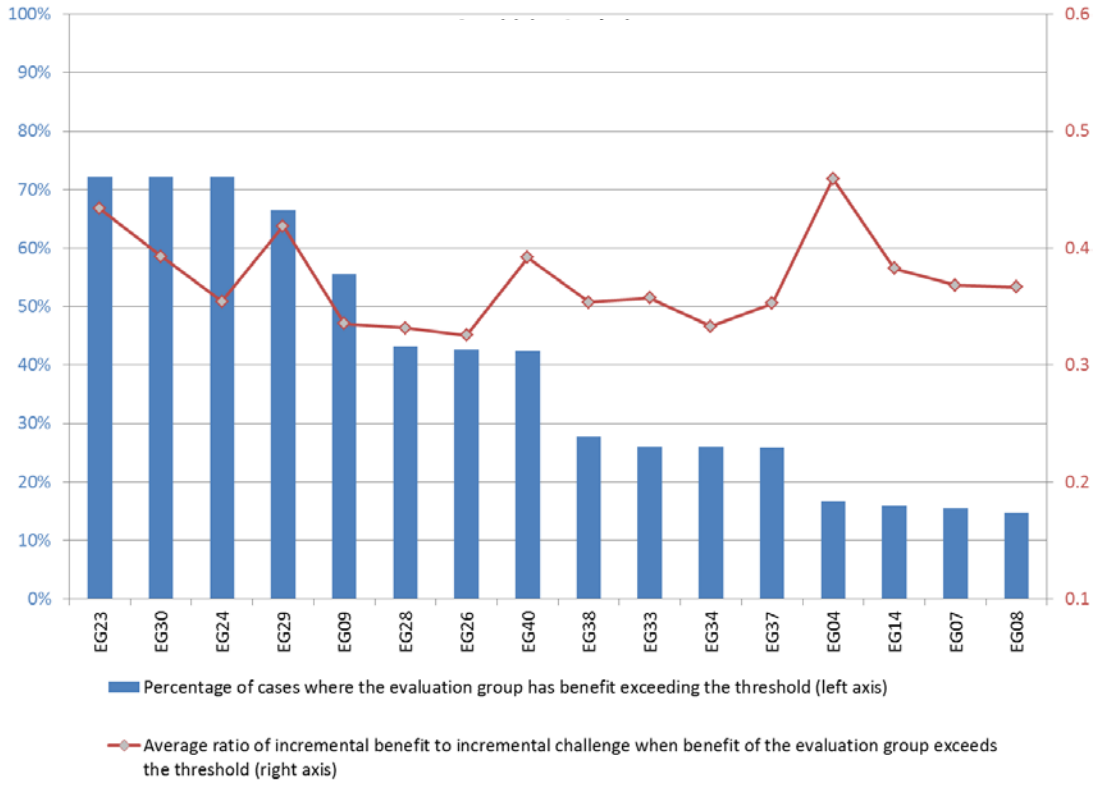


Figure F-2.1.2a. Sensitivity Results for Scenario 1, Higher Utility Threshold.

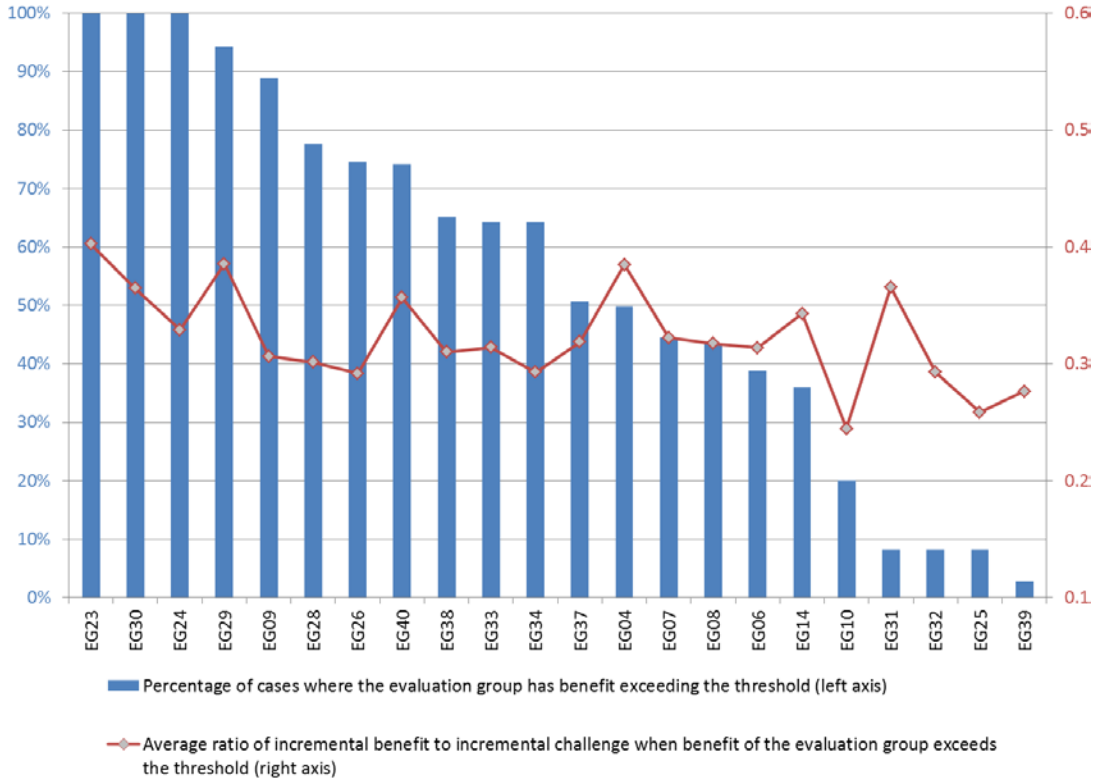


Figure F-2.1.2b. Sensitivity Results for Scenario 1, Second Utility Threshold.

Summary - Promising Groups, Supporting R&D, Technical Requirements, and Insights

Three Evaluation Groups have the highest benefit utility for this scenario, have high incremental benefit to incremental challenge ratios, and consistently perform better than all other Evaluation Groups in sensitivity analyses: Continuous recycle of U/Pu and U/TRU in fast critical reactors without enrichment (EG23 and EG24) and continuous recycle of U/TRU with both fast and thermal critical reactors without enrichment (EG30).

When expanding the promising set at less than the highest utility threshold, several once through, complete recycle, and some limited recycle options offer potential promise. When considering the challenge associated with achieving this potential promise, continuous recycle of U/Pu in fast critical reactors without enrichment (EG23) retains its high ranking among Evaluation Groups. However, when considering challenge with an expanded promising set of options, other options with lower promise and lower corresponding challenge, such as limited recycle of U/TRU to very high burnup in fast critical reactor without enrichment (EG09) and once-through U to very high burnup in fast critical reactor without enrichment (EG04), exhibit high rankings of incremental benefit to challenge ratio.

These promising Evaluation Groups are the same as those identified for the Nuclear Waste Management and Resource Utilization Criteria, so the same supporting R&D items indicated in Appendix E for those two criteria also apply to the promising options of this scenario. Those items are:

- 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.

F-2.2 Scenario 2 – Emphasize the Nuclear Waste Management Criterion

Definition of the Scenario: This scenario emphasizes change in the Nuclear Waste Management criterion over changes in the other three included benefit criteria.

Criteria Tradeoff Factors: This emphasis is implemented by assigning a tradeoff factor of 0.7 to the Nuclear Waste Management criterion and 0.1 to each of three other benefit criteria (Resource Utilization, Environmental Impact, and Safety criteria).

Results

The benefit and challenge results for this scenario for the 40 Evaluation Groups are presented graphically in Figure F-2.2.1.

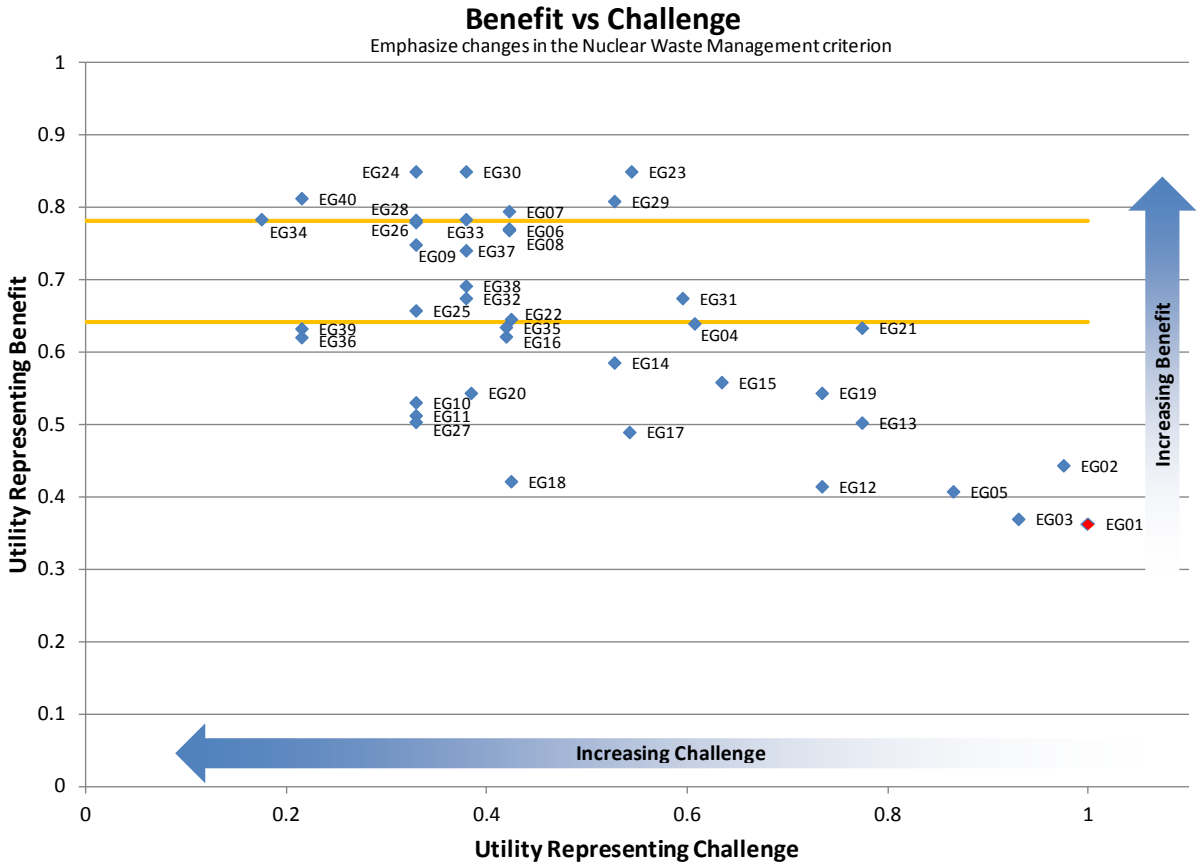


Figure F-2.2.1. Benefit versus Challenge Results for Scenario 2, Emphasize the Nuclear Waste Management Criterion, for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups based on benefit alone

The lists of potentially promising Evaluation Groups corresponding to benefit alone and defined threshold values are shown in Table F-2.2.1. For this scenario, three Evaluation Groups have the highest utility value (0.85), the same three Evaluation Groups that have the highest benefit utility values in Scenarios 1 and 3: continuous recycle of U/Pu and U/TRU in fast critical reactors without enrichment and continuous recycle of U/TRU with both fast and thermal critical reactors without enrichment (EG23, EG24, and EG30).

Table F-2.2.1. List of Promising Evaluation Groups by Benefit, Scenario 2.

Threshold Type	Evaluation Groups Within Threshold
Highest Possible Benefit Utility (0.85)	EG23, EG24, EG30
Promising groups based on highest utility score	
Threshold 1 (Benefit utility = 0.78; 0.42 higher than EG01)	EG07, EG23, EG24, EG28, EG29, EG30, EG33, EG34, EG40
Promising groups based on upper thresholds established for individual Criteria and proportioned by the criteria tradeoff factors defined for the Scenario	
Threshold 2 (Benefit utility = 0.64; 0.28 higher than EG01)	EG04, EG06, EG07, EG08, EG09, EG22, EG23, EG24, EG25, EG26, EG28, EG29, EG30, EG31, EG32, EG33, EG34, EG37, EG38, EG40
Promising groups based on lower thresholds established for individual Criteria (as applicable) and proportioned by the criteria tradeoff factors defined for the Scenario	
Color code	Once through / Limited recycle / Continuous recycle

For this scenario, two additional thresholds were defined as identifying potentially promising sets of Evaluation Groups, based on the two thresholds defined in Appendix E for Nuclear Waste Management, and the single thresholds defined for each of the other benefit criteria. Threshold 1 was defined by a benefit utility of at least 0.78 (0.42 better than the Basis of Comparison), and Threshold 2 was defined by a benefit utility of at least 0.64 (0.28 better than the Basis of Comparison).

As shown in Table F-2.2.1, Threshold 1 identified the three highest-utility Evaluation Groups and five additional continuous recycle systems: EG29 and EG33 (continuous recycle of Pu), EG34 (continuous recycle of TRU), and EG28 and EG40 (continuous recycle of ^{233}U). As indicated in Figure 2.2.1, EG26 (continuous recycle of ^{233}U in thermal reactors) was very near the Threshold 1 cutoff, and was captured in Threshold 2. EG07, a once-through fuel option for which a very high burnup fuel has been assumed, also meets this higher threshold value.

Threshold 2 adds three additional once-through options (EG04, EG06, and EG08), and one limited recycle option (EG09) all of which assume very high burnup fuel. Additional continuous recycle systems that meet this threshold include some, but not all, of the continuous recycle systems that met the lower threshold considering Nuclear Waste Management alone (See Appendix E, Table E-1.5). Three of the four Evaluation Groups that meet the lower threshold for Nuclear Waste Management alone, but which do not meet the threshold for this scenario (EG16, EG36, and EG39) are Evaluation Groups which have a higher safety challenge than the Basis of Comparison: even with a relatively low tradeoff factor on that criterion, it is sufficient to prevent those evaluation groups from reaching this lower threshold value. All the Evaluation Groups that meet Threshold 2 give at least a factor of five reduction in the mass of SNF+HLW to be disposed per energy generated relative to EG01, which was typically also the metric with the highest metric tradeoff factor.

Rankings considering both benefit and challenge

The ordered list of Evaluation Groups based on the benefit to challenge ratio is summarized in Table F-2.2.2 for each of the promising sets identified above. The numeric values indicate that EG23 and EG29 provide higher incremental benefit/challenge return than any other Evaluation Group. These are fuel cycle systems involving the continuous recycle of plutonium.

Table F-2.2.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio for Different Utility Thresholds, Scenario 2.

Highest possible utility ordered by incremental benefit/challenge ratio*		Threshold 1 groups ordered by incremental benefit/ challenge ratio*		Threshold 2 groups ordered by incremental benefit/ challenge ratio*	
EG23	1.07	EG23	1.07	EG23	1.07
EG30	0.78	EG29	0.94	EG29	0.94
EG24	0.73	EG30	0.78	EG30	0.78
		EG07	0.75	EG31	0.77
		EG24	0.73	EG07	0.75
		EG33	0.68	EG24	0.73
		EG28	0.63	EG08	0.71
		EG40	0.57	EG04	0.70
		EG34	0.51	EG06	0.70
				EG33	0.68
				EG28	0.63
				EG26	0.62
				EG37	0.61
				EG09	0.58
				EG40	0.57
				EG38	0.53
				EG34	0.51
				EG32	0.50
				EG22	0.49
				EG25	0.44

* "Incremental" is defined by the difference in performance, on the utility scale representing benefit, and on the utility scale representing challenge, between an Evaluation Group and Basis of Comparison (EG01).

Sensitivity analysis

Figure F-2.2.2 illustrates how the utility representing benefit changes as the Nuclear Waste Management Criteria Tradeoff factors is reduced from 1 (as in Appendix E) to "even" (0.25, as in Scenario 1). Evaluation Groups are ordered according to the ranking in Appendix E, representing a criteria tradeoff factor of 1 for Nuclear Waste Management. In contrast to the results for Scenario 3, emphasizing Resource Utilization, the utility values and the range of benefit utility benefit across Evaluation Groups for this scenario change more modestly as the criteria tradeoff factor changes, but the relative ordering of Evaluation Groups is more sensitive. These changes can be seen by the changes in the direction of the slope of each line as the tradeoff factor for Nuclear Waste Management is reduced below 1: slight changes in ordering can be seen even at tradeoff factors of 0.9 or 0.8. There is even some change in the top 10 Evaluation Groups based on the amount of emphasis placed on the Nuclear Waste Management criterion.

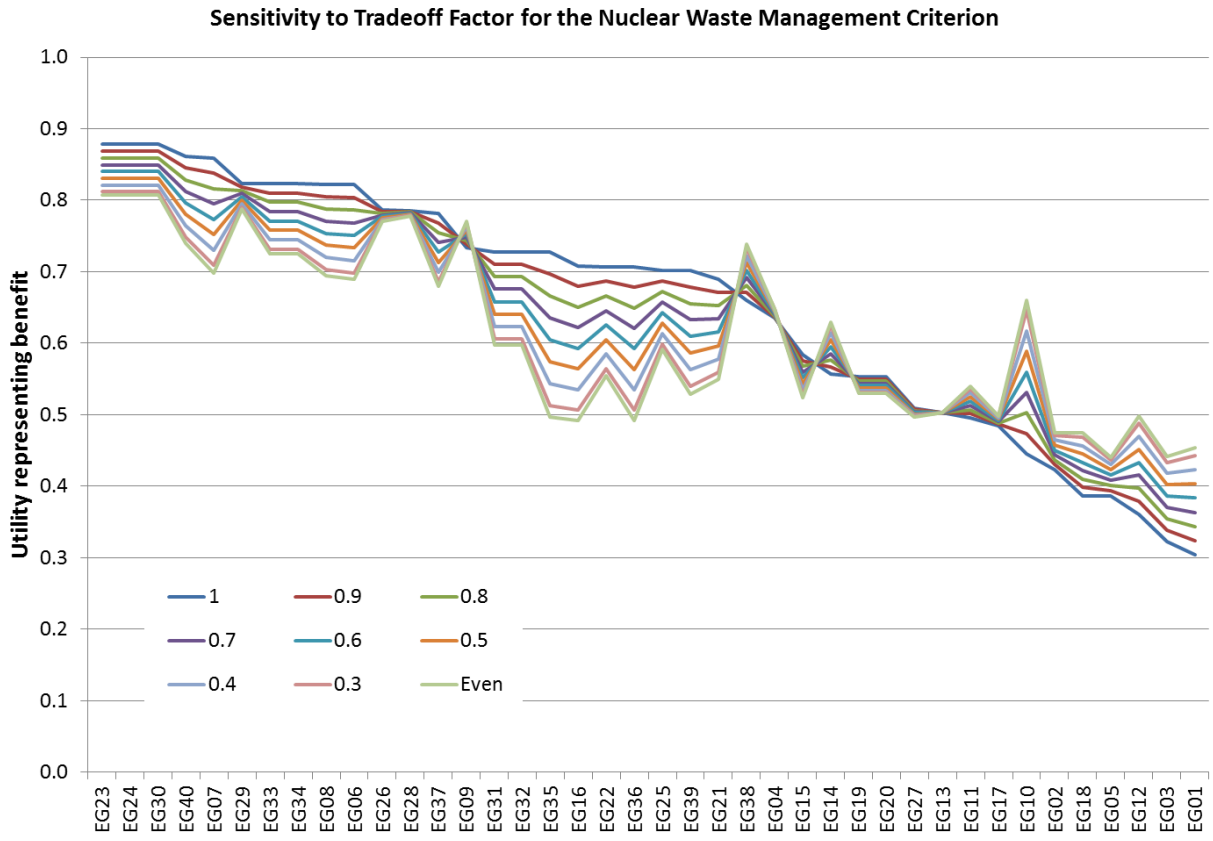


Figure F-2.2.2. Sensitivity of the Utility and Ranking of Evaluation Groups to Changes in the Emphasis on the Nuclear Waste Management Criterion.

Summary - Promising Groups, Supporting R&D, Technical Requirements, and Insights

Due to the similarity of the results in Table F-2.2.1 to those in Appendix E-1 (Table E-1.5) for the Nuclear Waste Management criterion, the same potential supporting R&D items indicated in that Appendix also apply to the promising options of this scenario that is emphasizing the Nuclear Waste Management criterion. Those items are:

- 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.

F-2.3 Scenario 3 – Emphasize the Resource Utilization Criterion

Definition of the Scenario: This scenario emphasizes change in the Resource Utilization criterion versus a balance of the other three benefit criteria considered in these scenario analyses.

Criteria Tradeoff Factors: This emphasis is implemented by assigning a tradeoff factor of 0.7 to the Resource Utilization criterion and 0.1 to each of three other benefit criteria (Environmental Impact, Nuclear Waste Management, and Safety criteria).

Results

The benefit and challenge results for this scenario are presented graphically in Figure F-2.3.1.

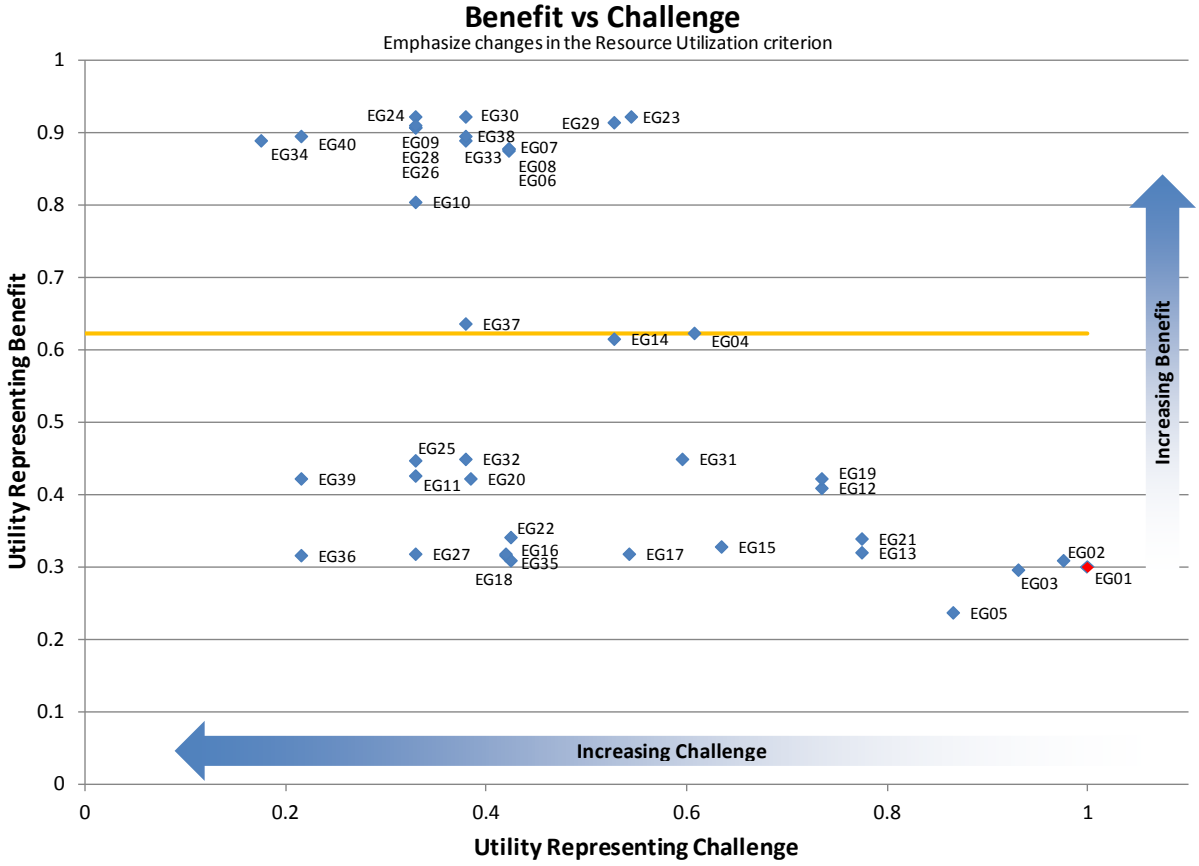


Figure F-2.3.1. Benefit versus Challenge Results for Scenario 3, Emphasize Resource Utilization, for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups based on benefit alone

The list of potentially promising Evaluation Groups that corresponds to benefit alone is shown in Table F-2.3.1. For this scenario, the highest utility value obtained by any Evaluation Group is 0.92. Only three Evaluation Groups have this utility value: EG23, EG24, and EG30 (continuous recycle of U/Pu and U/TRU in fast critical reactors without enrichment and continuous recycle of U/TRU with both fast and thermal critical reactors without enrichment).

For this scenario, only one threshold value (0.62, or 0.32 higher than the benefit utility for the Basis of Comparison) was considered, based on the one threshold identified for the Resource Utilization criterion in Appendix E and the lower threshold for the Nuclear Waste Management criterion. Eleven of the 17 Evaluation Groups meeting the threshold for promising options are continuous recycle systems. EG04,

EG06, EG07, EG08, EG09, and EG10 are once-through or limited recycle groups. Of the Evaluation Groups meeting the threshold, the set of EG06, EG08, EG10, EG26, EG28, EG38, and EG40, use thorium-only feeds. All the Evaluation Groups have analysis examples that do not use uranium enrichment, except for EG37, but even in that case, the portion of the overall nuclear fuel cycle requiring enriched uranium fuel is small (~12%).

Table F-2.3.1. List of Promising Evaluation Groups by Benefit, Scenario 3.

Threshold Type	**Evaluation Groups Within Threshold**
Highest Possible Benefit Utility (0.92)	EG23, EG24, EG30
Promising groups based on highest utility score	
Threshold 1 (Benefit utility = 0.62; 0.32 higher than EG01)	EG04, EG06, EG07, EG08, EG09, EG10, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG37, EG38, EG40
Promising groups based on thresholds established for individual Criteria and proportioned by the criteria tradeoff factors defined for the Scenario	
Color code	Once through / Limited recycle / Continuous recycle

These results are virtually identical to those obtained for the resource utilization criterion only in Appendix E-2.6 (Table E-2.6.3), leaving out only EG14, and identical to the results for threshold 2 of Scenario 1 with equal tradeoff factors for the included criteria. This suggests that resource utilization has a strong influence on the overall results. All of the Evaluation Groups that meet Threshold 1 for this scenario are identical to the Evaluation Groups in bins A and B of the natural uranium required metric (see Appendix D-2.14). In Appendix D-2.14, it was noted that these Evaluation Groups are those that give a factor of five or more reduction in the calculated natural uranium required, relative to the Basis of Comparison (EG01).

Rankings considering both benefit and challenge

The ordered list of Evaluation Groups based on the incremental benefit to challenge ratio for the highest utility groups and for the promising set defined by the threshold value is summarized in Table F-2.3.2. This consideration of the incremental benefit to challenge ratio results in an ordering of the Evaluation groups in which EG23 is first in the list, followed by EG29. These are fuel cycle systems involving the continuous recycle of uranium and plutonium. While the Evaluation Groups that meet the threshold value for this scenario are identical to those that meet the lower threshold for Scenario 1, the ranking by incremental benefit-to-challenge ratio varies slightly, due to the greater emphasis on Resource Utilization.

Table F-2.3.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio* for Different Utility Thresholds, Scenario 3.

Highest possible utility ordered by incremental benefit/challenge ratio		Threshold 1 groups ordered by incremental benefit/ challenge ratio	
EG23	1.36	EG23	1.36
EG30	1.00	EG29	1.30
EG24	0.93	EG30	1.00
		EG07	1.00
		EG08	1.00
		EG06	0.99
		EG38	0.96
		EG33	0.95
		EG24	0.93
		EG28	0.91
		EG09	0.90
		EG26	0.90
		EG04	0.82
		EG40	0.76
		EG10	0.75
		EG34	0.71
		EG37	0.54

* "Incremental" is defined by the difference in performance, on the utility scale representing benefit, and on the utility scale representing challenge, between an Evaluation Group and Basis of Comparison (EG01).

Sensitivity analysis

Figure F-2.3.2 illustrates how the utility representing benefit changes as the Resource Utilization Criteria tradeoff factor is reduced from 1 (equivalent to the analysis in Appendix E) to 0.25 (equivalent to Scenario 1 with equal emphasis on four benefit criteria). Evaluation Groups are ordered according to the ranking in Appendix E, representing a criteria tradeoff factor of 1 for Resource Utilization. Two important observations can be made from this figure. First, the absolute values of the utility representing benefit, and the range of utility across the Evaluation Groups varies significantly, especially for cases where the Resource Utilization is strongly emphasized by a high tradeoff factor. This suggests the potential for overall utility values and rankings to be strongly driven by the resource utilization criterion: it is one of few criteria that takes on utility values across almost the full range of 0 to 1, and thus with even a modest weighting (criteria tradeoff factor), can have significant influence on the final utility value. The ordering of Evaluation Groups does not change until the tradeoff factor for Resource Utilization is 0.4 or less, indicating that even modest "emphasis" on resource utilization will have a strong effect on Evaluation Group rankings. These changes in the ordering of Evaluation Groups can be seen by the change in the direction of the slope of each line: for tradeoff factors from 1.0 down to 0.5, the lines move continually down from left to right across the graph. When the tradeoff factor is 0.4, there is a change in order at EG22, shown by the increased slope in the "0.4" line in the figure. The ordering of the top 10 groups is unchanged across the full range of tradeoff factors explored. These sensitivity results suggest that the overall ranking of Evaluation Groups will be strongly correlated with the ranking based on resource utilization alone.

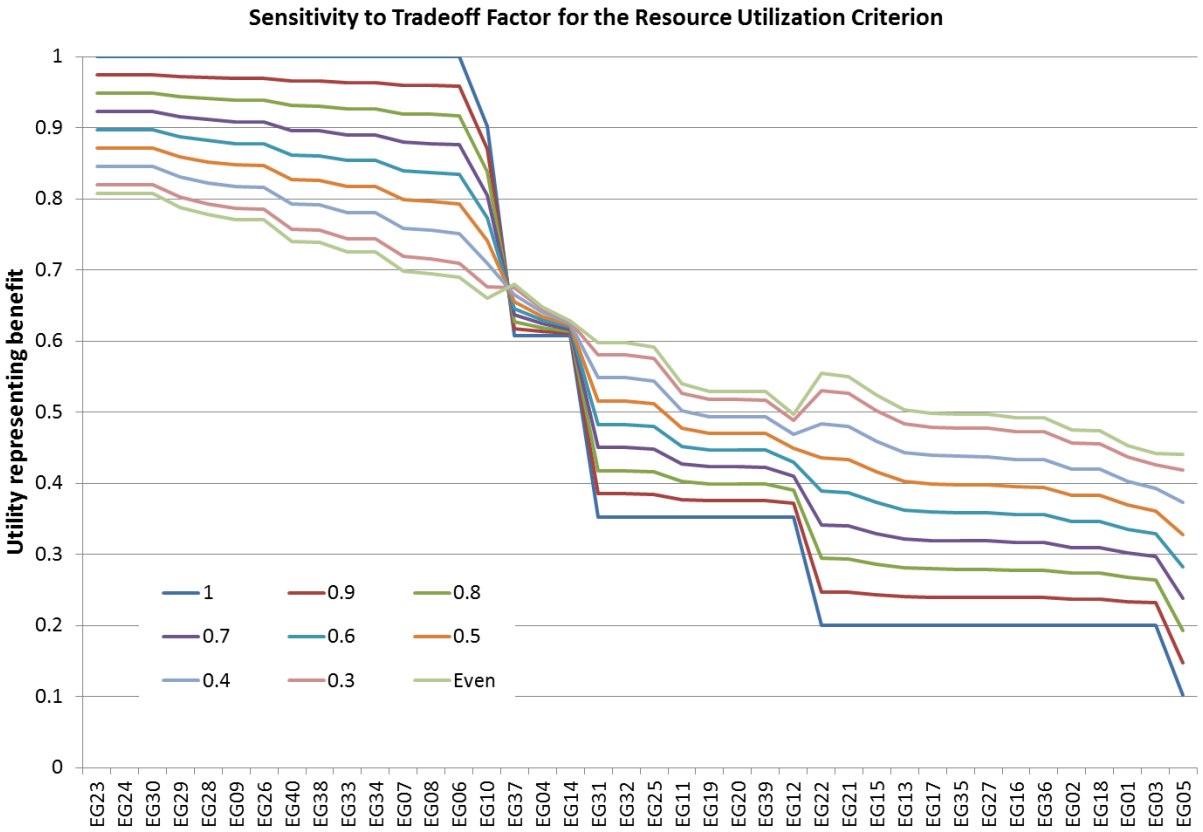


Figure F-2.3.2. Sensitivity of the Utility and Ranking of Evaluation Groups to Changes in the Emphasis on the Resource Utilization Criterion.

Summary - Promising Groups, Supporting R&D, Technical Requirements, and Insights

The results for this scenario are quite similar to those for Scenario 1, and very similar to those for the Resource Utilization criterion analysis in Appendix E, and the metric results in Appendix D-2.14. The potential supporting R&D items indicated in those Appendices also apply to the promising options of this scenario that is emphasizing resource utilization. Those items are:

- 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.

F-2.4 Scenario 4 – Emphasis on Changes in the Environmental Impact Criterion

Definition of the Scenario: This scenario emphasizes changes in the Environmental Impact criterion versus a balance of the other three included benefit criteria.

Criteria tradeoff factors: This emphasis is implemented by assigning a tradeoff factor of 0.7 to the Environmental Impact criterion and 0.1 to each of three other benefit criteria (Nuclear Waste Management, Resource Utilization, and Safety criteria).

Results

The benefit and challenge results for this scenario are presented in Figure F-2.4.1.

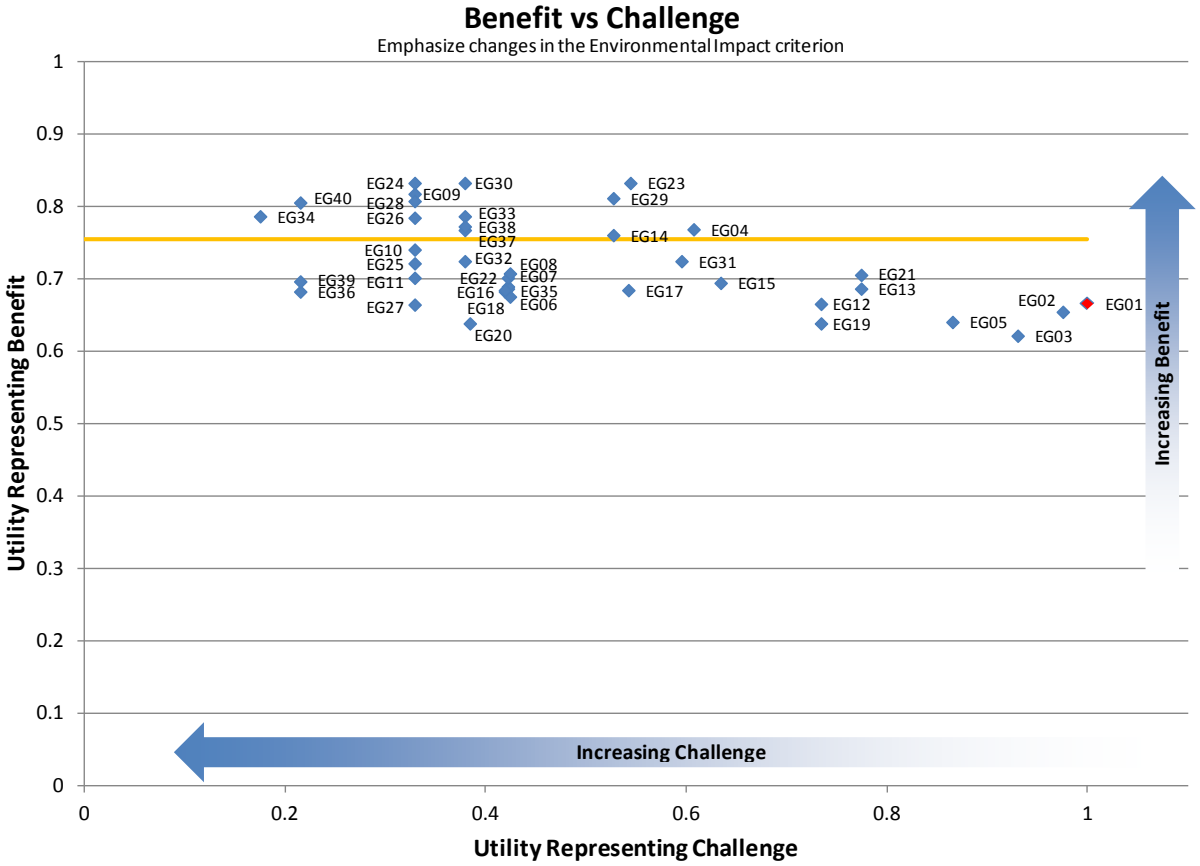


Figure F-2.4.1. Benefit versus Challenge Results for Scenario 4, Emphasize the Environmental Impact Criterion, for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups based on benefit alone

The list of potentially promising Evaluation Groups that corresponds to benefit alone is shown in Table F-2.4.1. For this scenario, the highest utility value obtained by any Evaluation Group is 0.83. Only three Evaluation Groups have this utility value and they are EG23, EG24, and EG30: continuous recycle of U/Pu and U/TRU in fast critical reactors without enrichment and continuous recycle of U/TRU with both fast and thermal critical reactors without enrichment.

In addition to considering the Evaluation groups with highest possible utility, two utility thresholds were defined based on the two thresholds identified for Nuclear Waste Management and the single thresholds identified for all other benefit criteria. The two threshold values are 0.77 (at least 0.10 greater than the

Basis of Comparison), and 0.75 (at least 0.08 greater than the Basis of Comparison). These two thresholds give identical results (i.e. the lower threshold did not result in the inclusion of any additional groups), so only the lower value is illustrated in Figure F-2.4.1 and in Table F-2.4.1.

Table F-2.4.1. List of Promising Evaluation Groups by Benefit, Scenario 4.

Threshold Type	Evaluation Groups Within Threshold
Highest Possible Utility Score (Utility = 0.83)	EG23 EG24 EG30
Promising groups based on highest utility score	
Threshold 1 (Utility = 0.75; 0.08 higher than EG01)	EG04 EG09 EG14 EG23 EG24 EG26 EG28 EG29 EG30 EG33 EG34 EG37 EG38 EG40
Promising groups based on thresholds established for individual Criteria and proportioned by Scenario weighting factors for each Criterion	
Color code	Once through / Limited recycle / Continuous recycle

The potentially promising set of Evaluation groups identified by this threshold includes not only continuous recycle options, but also once-through and limited recycle options. The once-through option identified was EG04. Limited recycle included EG09 and EG14. The continuous recycle options included EG23, EG24, and EG30, the highest utility options, as well as EG26, EG28, EG29, EG33, EG34, EG37, EG38, and EG40. These include both Uranium and thorium fueled systems. All except EG37 are without enrichment.

Rankings considering both benefit and challenge

Table F-2.4.2 shows a ranking of the Evaluation Groups within each of the two promising sets when accounting for the ratio of incremental benefit to the challenge of achieving that benefit. This listing shows high rankings of several continuous recycle Evaluation Groups including continuous recycle of U/Pu in fast critical reactors without enrichment (EG23) and continuous recycle of U/Pu with both fast and thermal critical reactors without enrichment (EG29). EG04 and EG30 have virtually the same Benefit to Challenge ratio, although examination of Figure F-2.4.1 shows that EG04 has lower benefit utility (and correspondingly less challenge) than EG30.

Table F-2.4.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio* for Different Utility Thresholds, Scenario 4.

Highest possible utility ordered by incremental benefit/challenge ratio		Threshold 1 / 2groups ordered by incremental benefit/challenge ratio	
EG23	0.36	EG23	0.36
EG30	0.27	EG29	0.31
EG24	0.25	EG30	0.27
		EG04	0.26
		EG24	0.25
		EG09	0.23
		EG28	0.21
		EG14	0.20
		EG33	0.19
		EG40	0.18
		EG26	0.18
		EG38	0.17

	EG37	0.16
	EG34	0.15

* "Incremental" is defined by the difference in performance, on the utility scale representing benefit, and on the utility scale representing challenge, between an Evaluation Group and Basis of Comparison (EG01).

Sensitivity analysis

Figure F-2.4.2 illustrates how the utility representing benefit changes as the tradeoff factor for the Environmental Impact Criterion is reduced from 1 (as in Appendix E) to 0.25 (as in Scenario 1). Evaluation Groups are ordered according to the ranking in Appendix E. When a tradeoff factor of 1 is used, equivalent to considering only the Environmental Impact Criterion, the difference between the highest and lowest benefit utility is small (about 0.3), relative to differences seen for the Resource Utilization Criterion (about 0.9) and the Nuclear Waste Management Criterion (about 0.6). This suggests that even with relatively strong emphasis, the impact of the Environmental Impact Criterion on the ranking of evaluation groups will be small. As can be seen in the right portion of the graph, there is a small set of Evaluation Groups (EG26, EG38, and EG10) that change from being worse than the Basis of Comparison (EG01) when only Environmental Impact is considered, to being better than the Basis of Comparison (EG01) when the relative emphasis on Environmental impact is reduced to even 0.9. This difference is greater as the criteria tradeoff factors become more alike. A similar change in utility and ordering can be seen for EG29. These results suggest that only a few Evaluation Groups are sensitive to the relative emphasis on the Environmental Impact criterion.

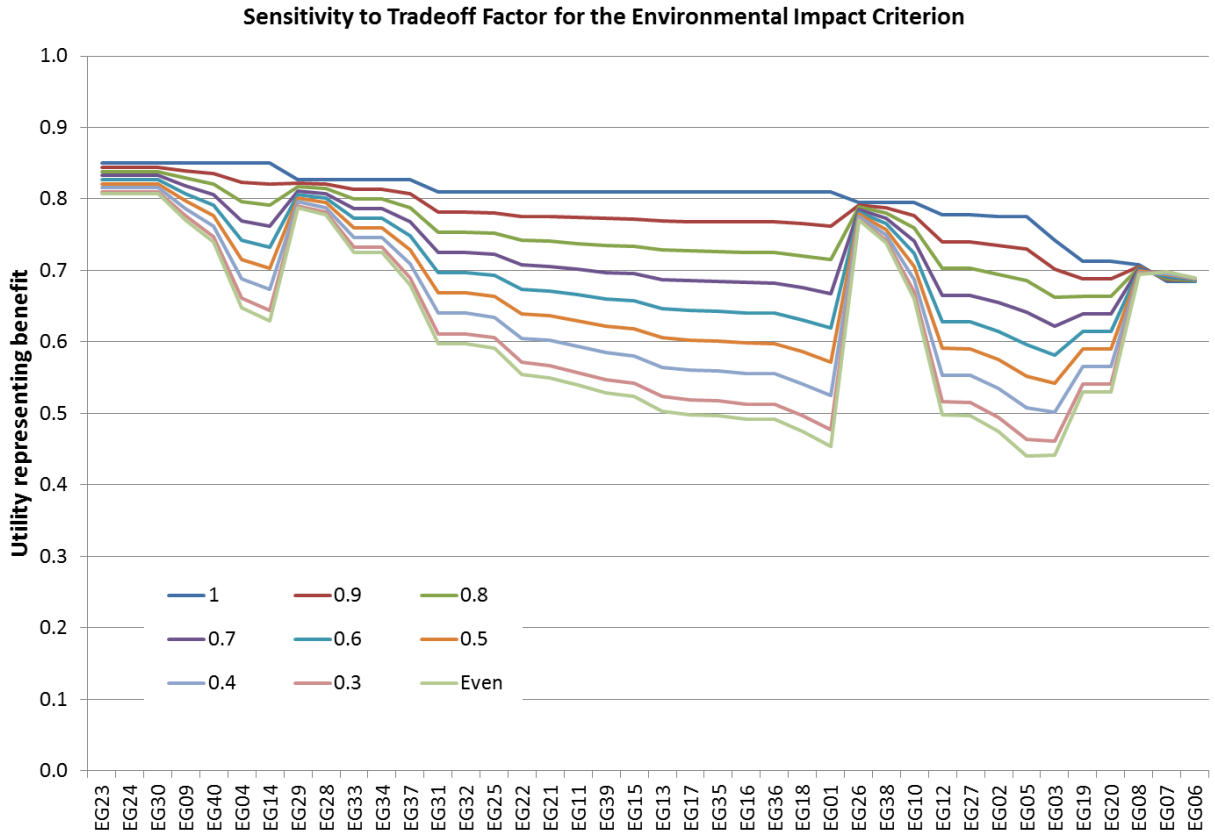


Figure F-2.4.2. Sensitivity of the Utility and Ranking of Evaluation Groups to Changes in the Emphasis on the Environmental Impact Criterion.

Summary - Promising Groups, Supporting R&D, Technical Requirements, and Insights

Continuous recycle of U/Pu and U/TRU in fast critical reactors without enrichment (EG23 and EG24) and continuous recycle of U/TRU with both fast and thermal critical reactors without enrichment (EG30) are among the Evaluation Groups with highest benefit utility. However, when expanding the promising sets at less than highest utility thresholds, several options representing once through, limit recycle and complete recycle offer potential promise. When considering the challenge associated with achieving this potential promise, continuous recycle of U/Pu in fast critical reactors without enrichment (EG23) retains its high ranking among Evaluation Groups. When considering challenge with an expanded promising set of options, other options with somewhat lower promise and lower corresponding challenge, such as limited recycle of U/TRU to very high burnup in fast critical reactors without enrichment (EG09) and once-through U to very high burnup in fast critical reactors without enrichment (EG04), exhibit high rankings of incremental benefit to challenge ratio.

Due to the fact that the Environmental Impact Criterion is the most influential for this scenario, the same potential supporting R&D items indicated in Appendix E for this criterion also apply to the promising options of this scenario. Those items are:

- 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.

F-2.5 Scenario 5 – Emphasize the Safety Criterion

Definition of the Scenario: This scenario emphasizes differences in the Safety criterion versus a balance of the other three included benefit criteria.

Criteria Tradeoff Factors: This emphasis is implemented by assigning a tradeoff factor of 0.7 to the Safety Criterion and 0.1 to each of the three other benefit criteria (Nuclear Waste Management, Resource Utilization, and Environmental Impact criteria).

Results

The benefit and challenge results for this scenario for the 40 Evaluation Groups are presented graphically in Figure F-2.5.1.

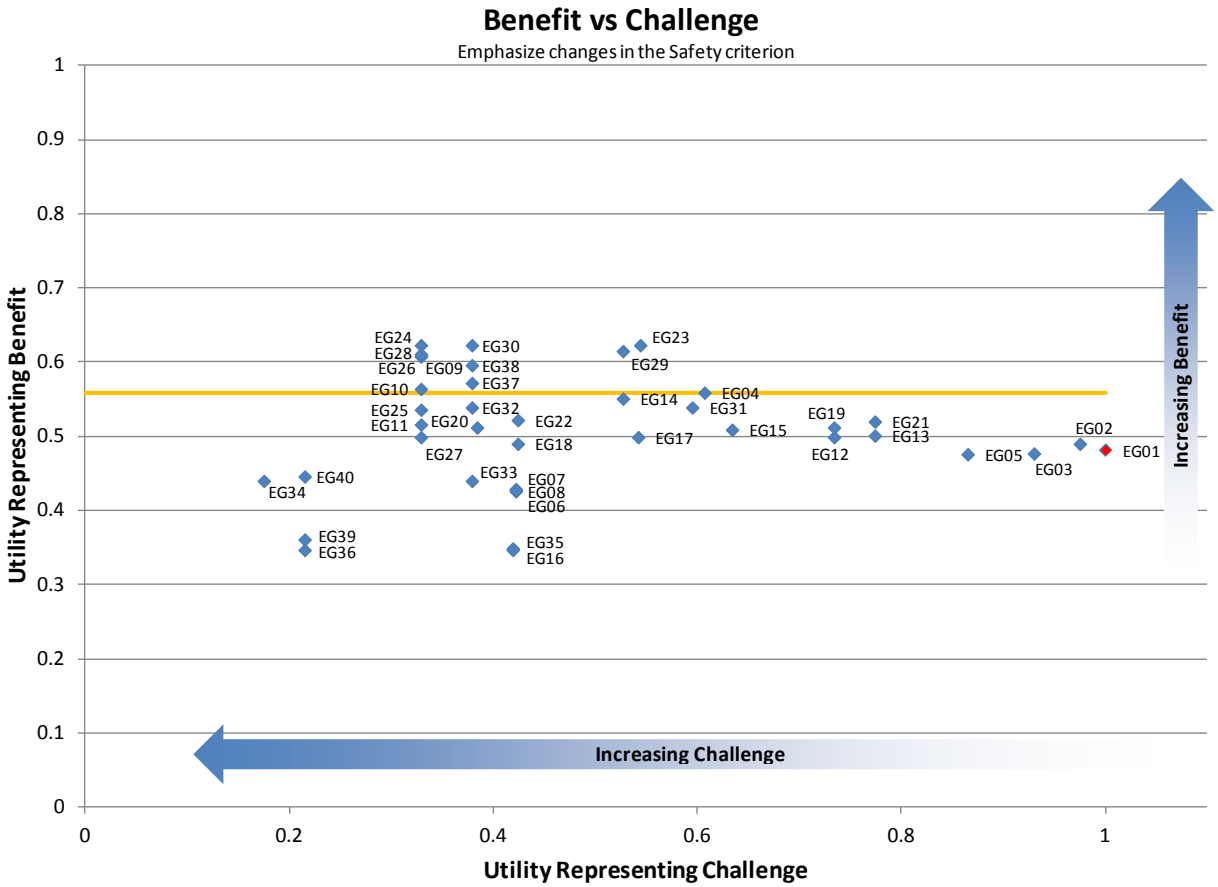


Figure F-2.5.1. Benefit versus Challenge Results for Scenario 5, Emphasize the Safety Criterion, for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups based on benefit alone

The list of potentially promising Evaluation Groups that correspond to the benefit alone is show in Table F-2.5.1. Two groups are identified: those with the highest benefit utility and those that exceed a threshold value based on the thresholds for the individual criteria using the criteria trade-off factors as described previously. Although no Evaluation Groups perform better than the Basis of Comparison on the Safety Criterion (as described in Appendix E), inclusion of Safety with a relatively high tradeoff factor does lead to different results than were seen in Scenario 1. Specifically, Evaluation Groups with sub-critical reactors are removed from the identified sets of promising groups because they are the only Evaluation Groups that rank lower than the Basis of Comparison for the Safety Criterion. This removes EG06, EG07, EG08, EG33, EG34, and EG40) from the set of potentially promising Evaluation Groups. The remaining results are driven by other criteria and the Evaluation Groups meeting Threshold 1 are the same as those that meet Threshold 2 for Scenario 1 (with the exception noted).

Rankings considering both benefit and challenge

The ordered lists of Evaluation Groups based on the incremental benefit to challenge are shown in Table F-2.5.2. Even though the promising set is smaller due to the elimination of Evaluation Groups with subcritical reactors, the ordering of the Evaluation Groups within each set is identical to the ordering of those Evaluation Groups in Scenario 1 for the second threshold.

Table F-2.5.1. List of Promising Evaluation Groups by Benefit, Scenario 5.

Threshold Type	Evaluation Groups Within Threshold
Highest Possible Benefit Utility (0.62)	EG23, EG24, EG30
Promising groups based on highest utility score	
Threshold 1 (Benefit utility = 0.56; 0.08 higher than EG01)	EG04, EG09, EG10, EG23, EG24, EG26, EG28, EG29, EG30, EG37, EG38
Promising groups based on thresholds established for individual Criteria and proportioned by the criteria tradeoff factors defined for the Scenario	
Color code	Once through / Limited recycle / Continuous recycle

Table F-2.5.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio* for Different Utility Thresholds, Scenario 5.

Highest possible utility via incremental benefit/challenge ratio		Threshold 1 groups via incremental benefit/ challenge ratio	
EG23	0.31	EG23	0.31
EG30	0.23	EG29	0.28
EG24	0.21	EG30	0.23
		EG24	0.21
		EG04	0.20
		EG28	0.19
		EG09	0.19
		EG26	0.19
		EG38	0.19
		EG37	0.15
		EG10	0.12

* "Incremental" is defined by the difference in performance, on the utility scale representing benefit, and on the utility scale representing challenge, between an Evaluation Group and Basis of Comparison (EG01).

Sensitivity analysis

Figure F-2.5.2 illustrates how the utility representing benefit changes as the criteria tradeoff factor for Safety is reduced from 1 (as in Appendix E) to "even" (0.25, as in Scenario 1). Evaluation Groups are ordered according to the ranking in Appendix E, representing a criteria tradeoff factor of 1 for Safety. As shown in Appendix E and illustrated by the "step" in the results with a tradeoff factor of 1 (between EG05 and EG40), the Safety Criterion identifies two sets of Evaluation Groups. Within each of these sets, the ordering of Evaluation Groups is determined by the other criteria. When the tradeoff factor for Safety is reduced to 0.6 or lower, the impact of those other criteria is sufficient to outweigh the reduction in utility associated with the increased safety challenge for some Evaluation Groups. This is the case at EG40: with a tradeoff factor of 0.7, it has lower benefit utility than EG05, and with a tradeoff factor of 0.6 it has a higher benefit utility. These sensitivity results suggest that the Safety Criterion has the potential to have a significant effect on the overall ranking of those groups with higher safety challenge, depending in part on how much emphasis is placed on the importance of the differences between fuel cycles in terms of the challenge of meeting safety requirements.

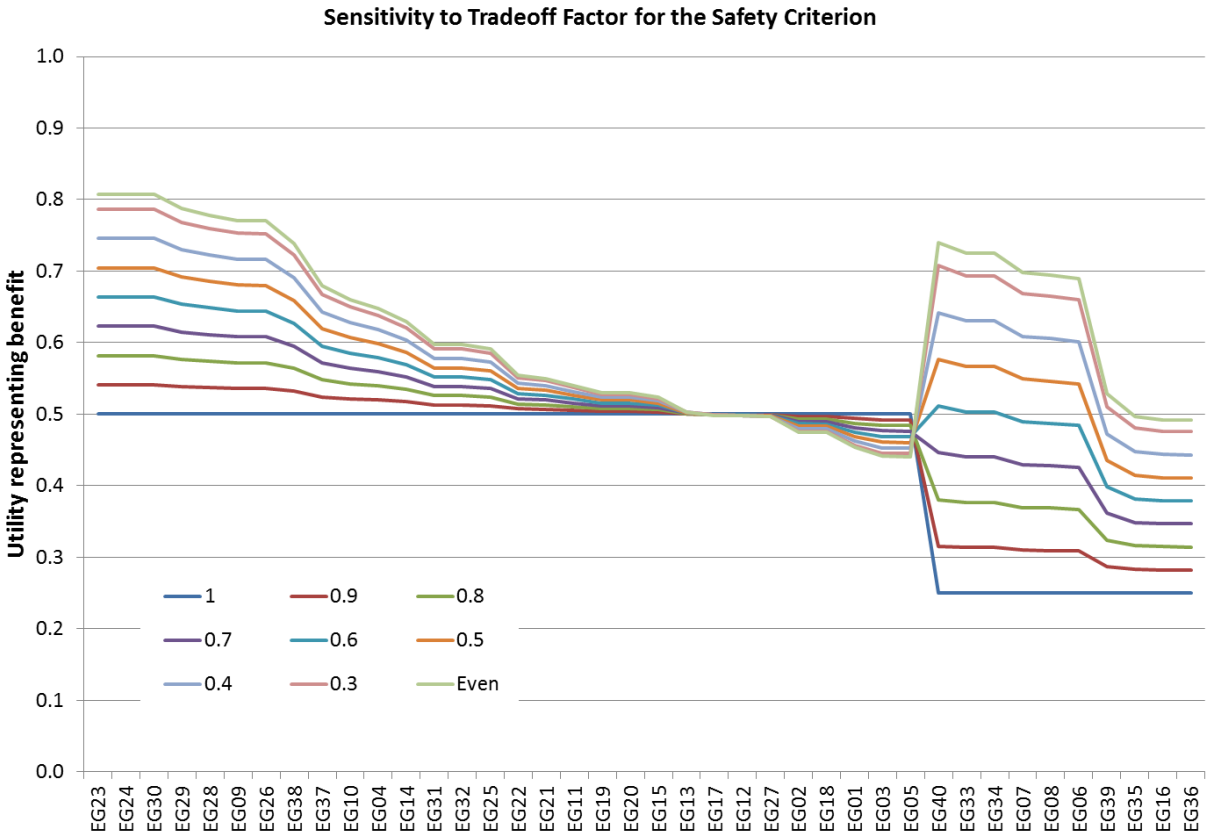


Figure F-2.5.2. Sensitivity of the Utility and Ranking of Evaluation Groups to Changes in the Emphasis on the Safety Criterion.

Summary – Most promising groups, Supporting R&D, Technical Requirements, and Insights

The promising groups identified for this scenario are similar to those identified for Scenario 1, with the emphasis on the Safety Criterion serving to remove those Evaluation Groups with sub-critical reactors from the promising set. The remaining Evaluation Groups in the promising set are determined by the other benefit criteria, primarily Nuclear Waste Management and Resource Utilization.

F-2.6 Scenario 6 – Emphasize Reducing the Physical Impacts of Producing Nuclear Power

Definition: of the Scenario: Emphasize the importance of differences in the Nuclear Waste Management, Resource Utilization, and Environmental Impact criteria – to focus on the direct physical impacts of producing nuclear power and the potential to reduce those impacts by choice of fuel cycle.

Criteria Tradeoff Factors: This emphasis is implemented by assigning equal criteria tradeoff factors of ~0.33 to each of the included criteria, and a tradeoff factor of zero to the Safety criterion.

Results

The benefit and challenge results for this scenario are presented graphically in Figure F2.6.1

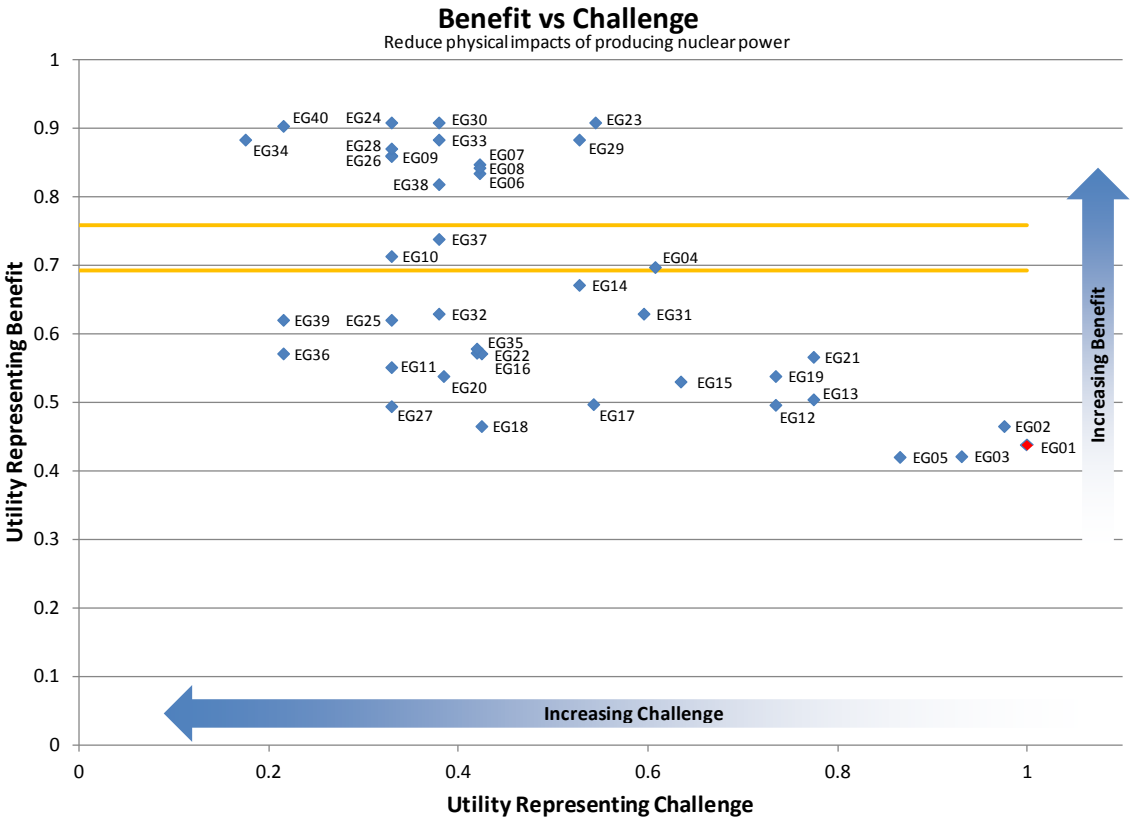


Figure F-2.6.1. Benefit versus Challenge Results for Scenario 6, Emphasize Reducing the Impacts of Producing Nuclear Power, for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups based on benefit alone

The list of potentially promising Evaluation Groups that corresponds to benefit alone is shown in Table F-2.6.1. In addition to considering the Evaluation Groups with highest possible benefit utility, two utility thresholds were defined as illustrated in Figure F-2.6.1 and described in the Table F-2.6.1. The first set includes 14 promising Evaluation Groups while the second set includes 17 Evaluation Groups. These results are virtually identical to the results in Scenario 1.

Table F-2.6.1. List of Promising Evaluation Groups by Benefit, Scenario 6.

Threshold Type	Evaluation Groups Within Threshold
Highest Possible Benefit Utility (0.909)	EG23 EG24 EG30
Promising groups based on highest utility score	
Threshold 1 (Benefit utility = 0.759; 0.32 higher than EG01)	EG06 EG07 EG08 EG09 EG23 EG24 EG26 EG28 EG29 EG30 EG33 EG34 EG38 EG40
Promising groups based on upper thresholds established for individual Criteria and proportioned by the criteria tradeoff factors defined for the Scenario	
Threshold 2 (Benefit utility = 0.691; 0.25 higher than EG01)	EG04 EG06 EG07 EG08 EG09 EG10 EG23 EG24 EG26 EG28 EG29 EG30 EG33 EG34 EG37 EG38 EG40
Promising groups based on lower thresholds established for individual Criteria (as applicable) and proportioned by the criteria tradeoff factors defined for the Scenario	
Color code	Once through / Limited recycle / Continuous recycle

Several once through options, such as once-through Th to very high burnup in thermal EDS (EG06), once-through U to very high burnup in thermal or fast EDS without enrichment (EG07), and once-through Th to very high burnup in fast EDS (EG08) are in the potentially promising set, although only certain continuous recycle groups (EG23, EG24, and EG30) have the highest possible benefit utility.

Rankings considering both benefit and challenge

The ordered list of Evaluation Groups based on the ratio of incremental benefit to incremental challenge is summarized in Table F-2.6.2 for each of the promising sets identified above. Although the list of potentially promising Evaluation Groups in this scenario is nearly identical to the corresponding lists in Scenario 1, the ordering of Evaluation Groups with those sets is slightly different. As can be seen by comparing the table below to Table F-2.1.2 for Scenario 1, several once through Evaluation Groups (EG07, EG08, and EG06) rank higher in this scenario than in Scenario 1. The rankings are otherwise quite similar.

Table F-2.6.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio for Different Utility Thresholds, Scenario 6.

Highest possible utility via incremental benefit/challenge ratio*		Threshold 1 groups via incremental benefit/ challenge ratio*		Threshold 2 groups via incremental benefit/ challenge ratio*	
EG23	1.03	EG23	1.03	EG23	1.03
EG30	0.76	EG29	0.94	EG29	0.94
EG24	0.70	EG30	0.76	EG30	0.76
		EG33	0.72	EG33	0.72
		EG07	0.71	EG07	0.71
		EG24	0.70	EG24	0.70
		EG08	0.70	EG08	0.70
		EG06	0.69	EG06	0.69
		EG28	0.65	EG04	0.66
		EG09	0.63	EG28	0.65
		EG26	0.63	EG09	0.63
		EG38	0.61	EG26	0.63
		EG40	0.59	EG38	0.61
		EG34	0.54	EG40	0.59
				EG34	0.54
				EG37	0.48
				EG10	0.41

* "Incremental" is defined by the difference in performance, on the utility scale representing benefit, and on the utility scale representing challenge, between an Evaluation Group and Basis of Comparison (EG01).

Sensitivity analyses

Figures F-2.6.2(a-b) illustrates the sensitivity analysis results considering each of the two thresholds defined above for identifying the promising set. In this scenario, eight Evaluation Groups are robust to the various perspectives: EG23, EG40, EG30, EG24, EG29, EG33, EG34, and EG09 exceed threshold 1 for 50% of perspectives and exceed threshold 2 for nearly 90% of perspectives considered. In addition, several Evaluation Groups appear in the promising set for this scenario more often than was the case for Scenario 1, and the absolute values of the average ratio of incremental benefit to challenge are higher in this scenario. All of these differences can be attributed to the slightly higher tradeoff factors used for the Criteria that show the greatest differences across the Evaluation Groups, the Nuclear Waste Management and Resource Utilization criteria.

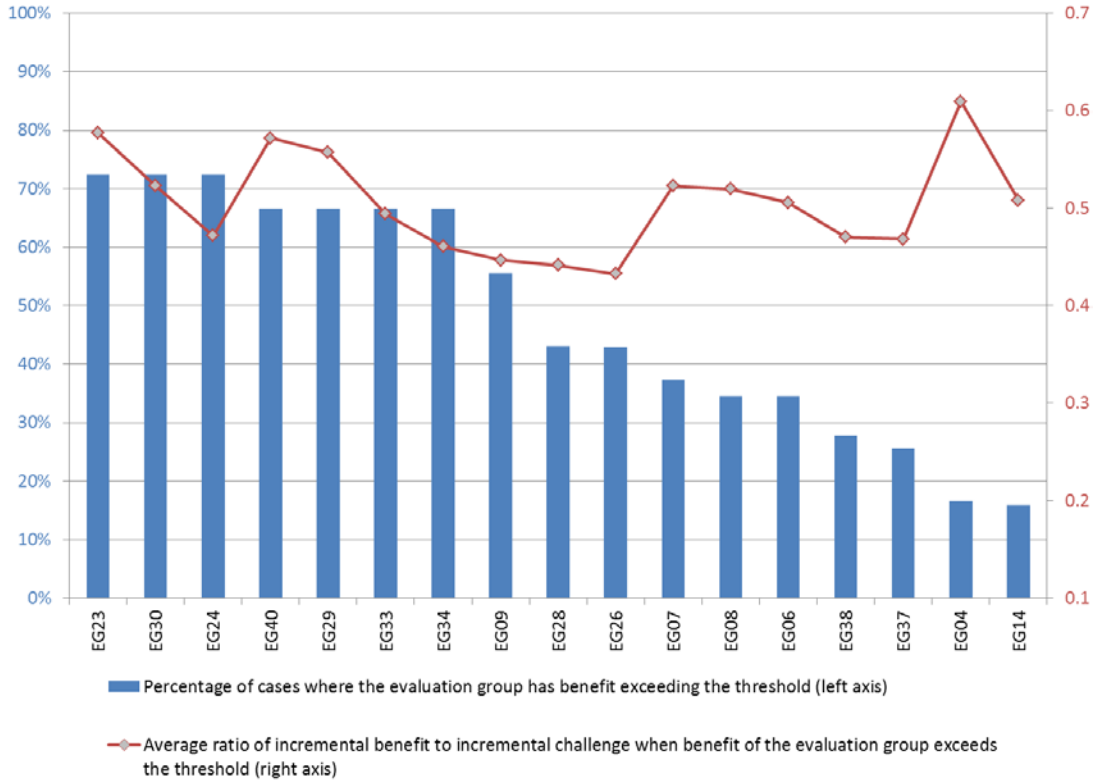


Figure F-2.6.2a. Sensitivity Results for Scenario 6, Higher Utility Threshold.

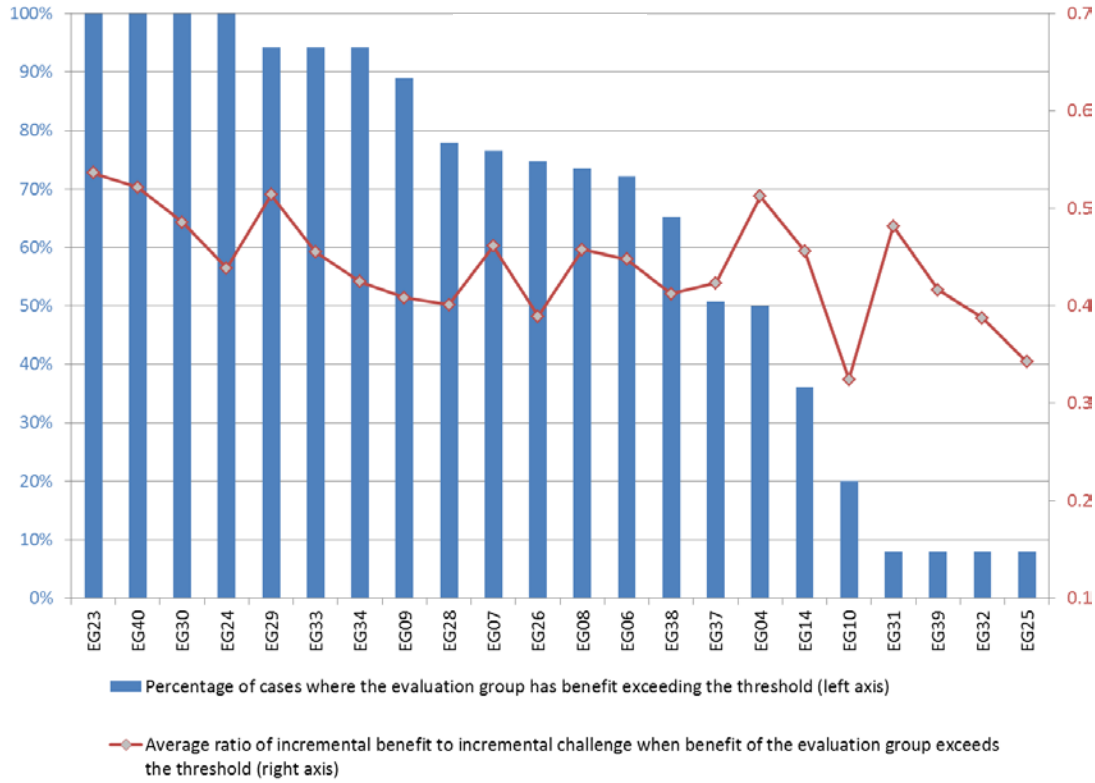


Figure F-2.6.2b. Sensitivity Results for Scenario 6, Second Utility Threshold.

Summary: Most Promising Groups, Supporting R&D, Technical Requirements, and Insights

Results of this scenario have many similarities to the equal tradeoff factor perspective of Scenario 1. With the exception of limited recycle of U/TRU to very high burnup in fast critical reactor without enrichment (EG09), once-through Th to very high burnup in thermal EDS (EG06), once-through U to very high burnup in thermal or fast EDS without enrichment (EG07), and once-through Th to very high burnup in fast EDS (EG08), the upper threshold of top performers is composed of full recycle groups. Evaluation Groups of highest utility are continuous recycle of U/Pu and U/TRU in fast critical reactors without enrichment (EG23 and EG24) and continuous recycle of U/TRU with both fast and thermal critical reactors without enrichment (EG30). When considering the challenge associated with achieving this potential benefit, continuous recycle of U/Pu in fast critical reactors without enrichment (EG23) retains its high ranking among evaluation groups. However, when considering challenge, some once through options with lower benefit and lower corresponding challenge, such as once-through Th to very high burnup in thermal EDS (EG06), once-through U to very high burnup in thermal or fast EDS without enrichment (EG07), once-through Th to very high burnup in fast EDS (EG08), and once-through U to very high burnup in fast critical reactor without enrichment (EG04) exhibit high rankings. As with equal criteria tradeoff factors (Scenario 1), this scenario is influenced primarily by the Nuclear Waste Management and Resource Utilization criteria, leading to the same potential supporting R&D items. Those items are:

- 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.

F-2.7 Scenario 7 – Emphasis on Nuclear Waste Management, Resource Utilization, and Safety Criteria

Definition of Scenario: Emphasize the importance of differences in three of the benefit criteria, excluding Environmental Impact – to explore the impact of the benefit criteria of Nuclear Waste Management, Resource Utilization, and Safety, without the consideration of Environmental Impact.

Criteria tradeoff factors: This emphasis is implemented by assigning equal tradeoff factors of ~0.33 to each of the included criteria (Nuclear Waste Management, Resource Utilization, and Safety) and a tradeoff factor of zero to the Environmental Impact Criterion.

Results

The benefit and challenge results for this scenario for the 40 Evaluation Groups are presented graphically in Figure F-2.7.1.

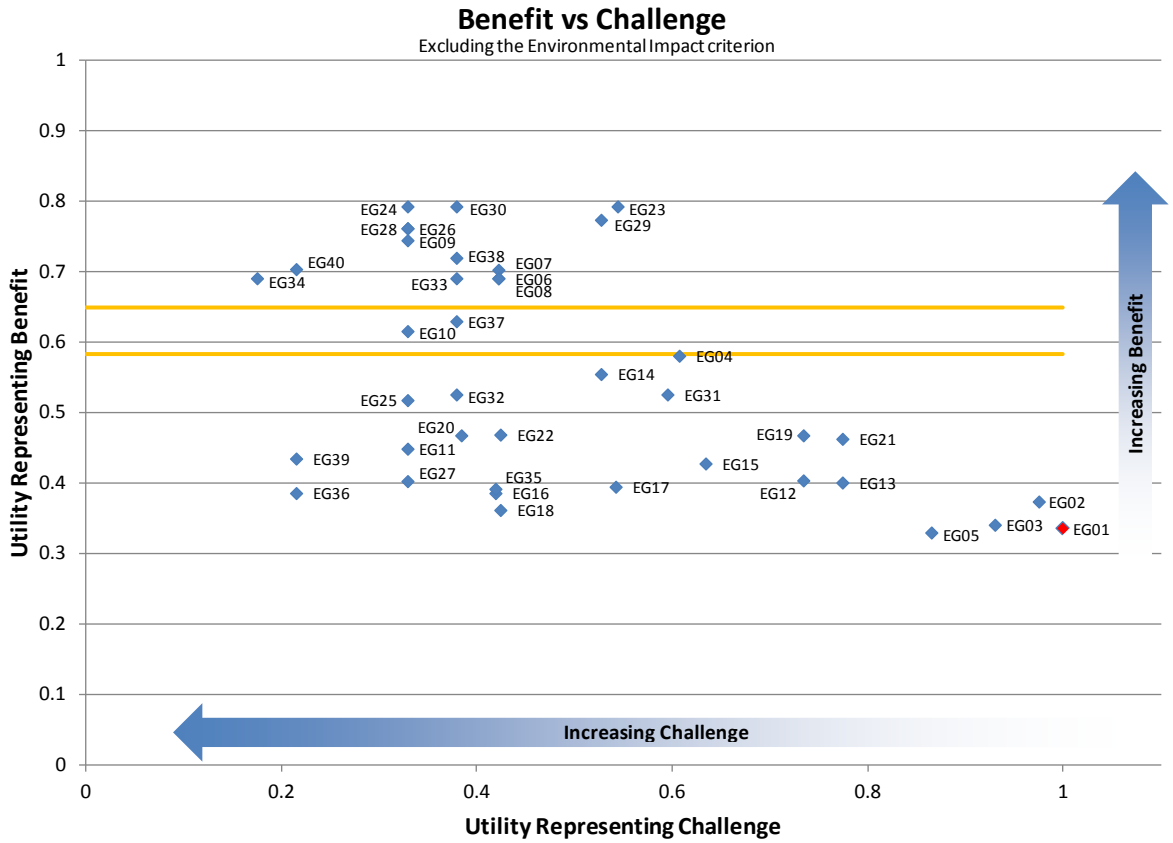


Figure F-2.7.1. Benefit versus Challenge Results for Scenario 7, Emphasis on Elimination of Environmental Impact Criterion for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups based on benefit alone

The list of potentially promising Evaluation Groups that correspond to the benefit alone is show in Table F-2.7.1. The thresholds for defining the potentially promising set are based on those Evaluation Groups that have the overall highest possible utility score and a combination of the thresholds for the individual criteria using the criteria trade-off factors.

Table F-2.7.1. List of Promising Evaluation Groups by Benefit, Scenario 7.

Threshold Type	Evaluation Groups Within Threshold
Highest Possible Benefit Utility (0.79)	EG23, EG24, EG30
Promising groups based on highest utility score	
Threshold 1 (Benefit utility = 0.65; 0.32 higher than EG01)	EG06, EG07, EG08, EG09, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG38, EG40
Promising groups based on upper thresholds established for individual Criteria and proportioned by the criteria tradeoff factors defined for the Scenario	
Threshold 2 (Benefit utility = 0.58; 0.25 higher than EG01)	EG06, EG07, EG08, EG09, EG10, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG37, EG38, EG40
Promising groups based on lower thresholds established for individual Criteria (as applicable) and proportioned by the criteria tradeoff factors defined for the Scenario	
Color code	Once through / Limited recycle / Continuous recycle

The results for this scenario are dominated by the Resource Utilization and Nuclear Waste Management Criteria. The results of potentially promising groups is identical to the list of promising options for Scenario 10, which emphasizes Nuclear Waste Management and Resource Utilization alone, again demonstrating the dominance of the Nuclear Waste Management and Resource Utilization Criteria in these scenarios. As with Scenario 10, it should be noted that EG04 (once-through U to very high burnup in fast critical reactor without enrichment) was just below the Threshold 2 for potentially promising options for the initial set of shape functions and tradeoff factors. The sensitivity analyses, provided below, show that as shape functions and tradeoff factors are varied, EG04 is frequently captured within the promising set.

Rankings considering both benefit and challenge

The ordered list of Evaluation Groups based on the benefit to challenge ratio is summarized in Table F-2.7.2 for the thresholds of 0.65 (Threshold 1) and 0.58 (Threshold 2). This consideration for the benefit-to-challenge ratio results in an ordering of groups in which EG23 and EG29 are clearly the leading ones. These are fuel cycle systems involving the continuous recycle of plutonium. However, unlike Scenario 8, which emphasizes Nuclear Waste Management and Resource Utilization Criteria, fuel cycles include TRU recycling options (EG30 and EG24) are relatively highly ranked.

Table F-2.7.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio for Different Utility Thresholds, Scenario 7.

Highest possible utility via incremental benefit/challenge ratio*		Threshold 1 groups via incremental benefit/ challenge ratio*		Threshold 2 groups via incremental benefit/ challenge ratio*	
EG23	1.00	EG23	1.00	EG23	1.00
EG30	0.74	EG29	0.93	EG29	0.93
EG24	0.68	EG30	0.74	EG30	0.74
		EG24	0.68	EG24	0.68
		EG07	0.64	EG07	0.64
		EG26	0.64	EG26	0.64
		EG28	0.64	EG28	0.64
		EG38	0.62	EG38	0.62
		EG06	0.62	EG06	0.62
		EG08	0.62	EG08	0.62
		EG09	0.61	EG09	0.61
		EG33	0.57	EG33	0.57
		EG40	0.47	EG37	0.48
		EG34	0.43	EG40	0.47
				EG34	0.43
				EG10	0.42

Sensitivity analyses

Figures F-2.7.2(a-b) illustrates the sensitivity analysis results considering each of the two thresholds defined above for identifying the promising set. The Environmental Impact Criterion, excluded from consideration in this scenario, has the smallest difference in utility values across the Evaluation Groups, so it is not surprising that the results of this scenario are very similar to those of Scenario 1. Differences can be seen primarily in the increased robustness of EG06, EG07, and EG08 in this scenario, and the decrease in robustness of EG04. As shown in Appendix E, EG06, EG07, and EG08 have the worst performance of all evaluation groups on the Environmental Impact Criterion, so when it is excluded from

consideration in this scenario, those evaluation groups perform better. EG04 has the best performance on the Environmental Impact Criterion, so excluding it from consideration has the opposite effect, decreasing its performance and robustness.

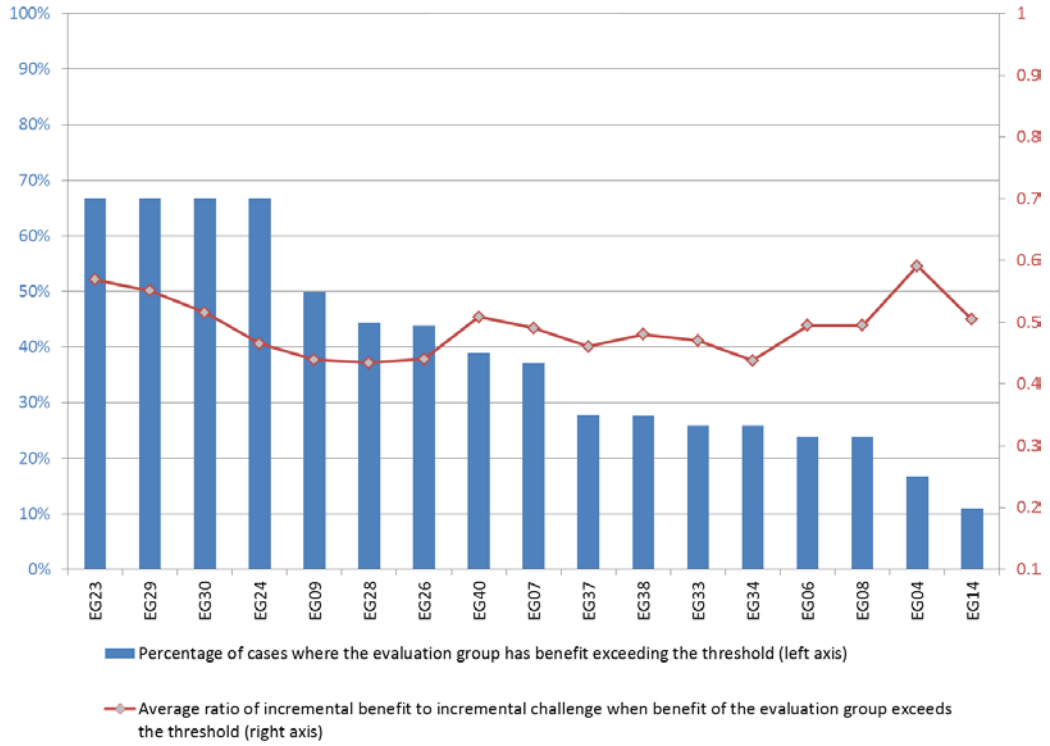


Figure F-2.7.2a. Sensitivity Results for Scenario 7, Higher Utility Threshold.

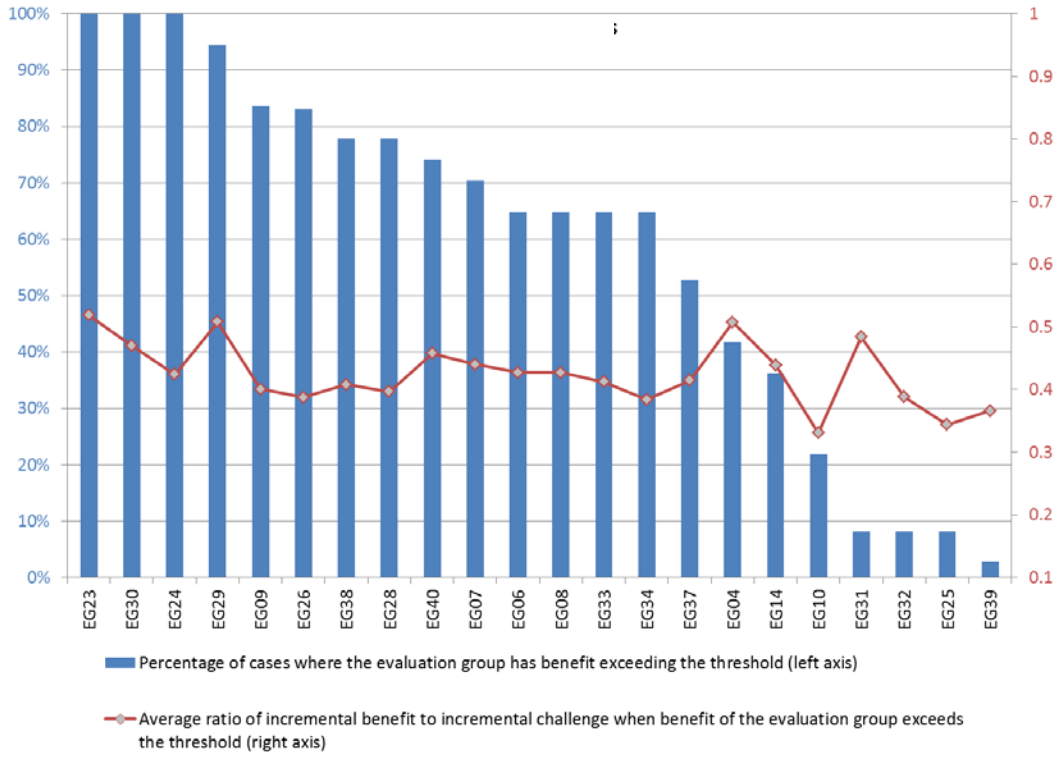


Figure F-2.7.2b. Sensitivity Results for Scenario 7, Second Utility Threshold.

Summary – Most promising groups, Supporting R&D, Technical Requirements, and Insights

The promising groups identified for this scenario are similar to those identified for Scenario 1 with the inclusion of Resource Utilization and Nuclear Waste Management strongly influencing the outcome.

F-2.8 Scenario 8 – Emphasis on Unlimited Natural Fuel Resources

Definition of the Scenario: This scenario de-emphasizes the differences between fuel cycle options arising from resource utilization in order to explore the potential impact of expanded fuel resource availability (such as uranium from seawater), while considering three other benefit criteria (Nuclear Waste Management, Environmental Impact, and Safety). Consequently, this scenario emphasizes unlimited resources. This scenario also serves as a test of the sensitivity of including the Resource Utilization criterion.

Criteria Tradeoff Factors: This emphasis is implemented by assigning a tradeoff factor of ~0.33 to each of the included criteria, and a tradeoff factor of zero to the Resource Utilization criterion.

Results

The benefit and challenge results for this scenario for the 40 Evaluation Groups are presented graphically in Figure F-2.8.1.

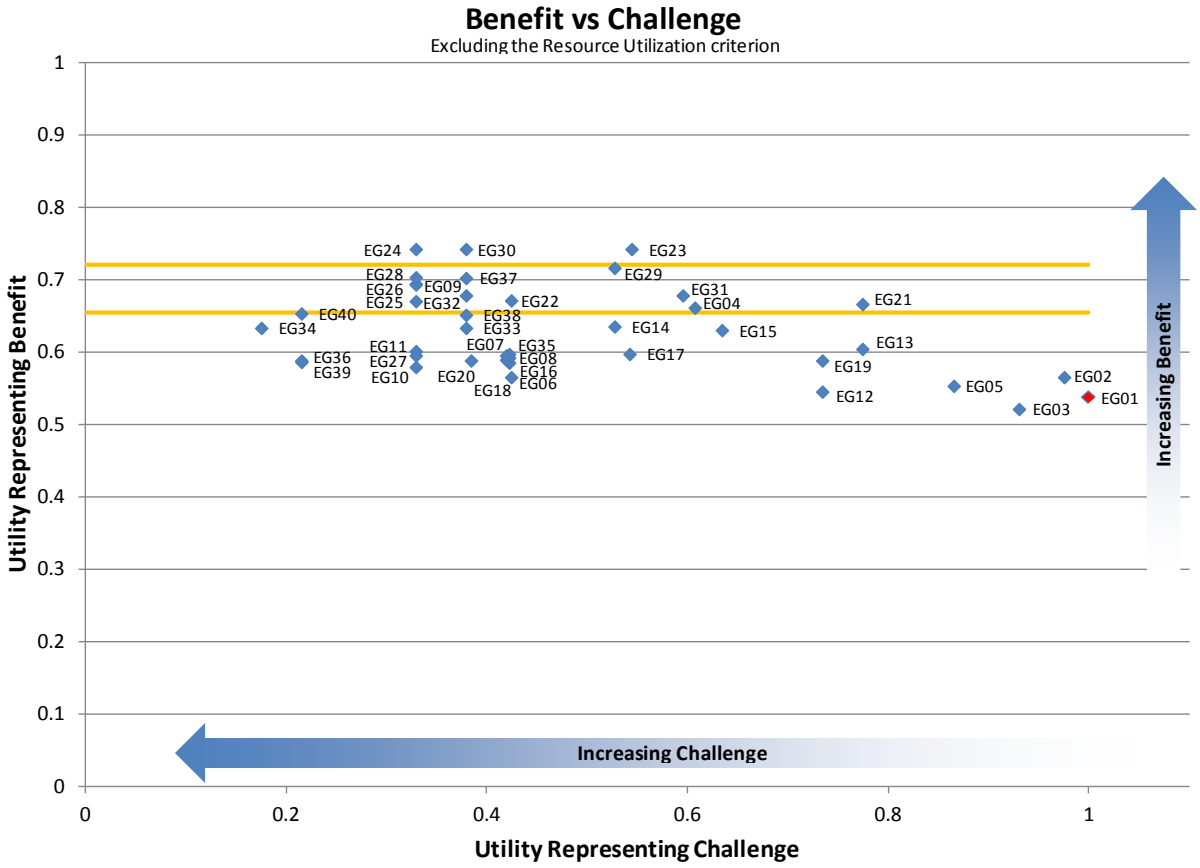


Figure F-2.8.1. Benefit versus Challenge Results for Scenario 8, Unlimited Natural Resources, for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups based on benefit alone

The list of potentially promising Evaluation Groups that corresponds to benefit alone is shown in Table F-2.8.1. For this scenario, the highest utility value obtained by any evaluation group is 0.74. As with most of the other scenarios, only three Evaluation Groups have this utility value: EG23, EG24, and EG30, which are fuel cycle systems involving the continuous recycle of Pu or TRU.

In addition to considering the Evaluation Groups with the highest possible benefit utility, two thresholds were defined as identifying potentially promising sets of Evaluation Groups. The two thresholds were defined, based on the two thresholds identified for the Nuclear Waste Management criterion and the single threshold defined for the other benefit criteria, using the method described in Section F-1.2. Threshold 1 was defined by a benefit utility of at least 0.72 (at least 0.18 higher than the Basis of Comparison), and Threshold 2 was defined by a benefit utility of at least 0.66 (0.12 higher than the Basis of Comparison).

Threshold 1 did not yield any additional Evaluation Groups that can be considered potentially promising beyond those identified by the highest utility group, and is therefore not shown in Table F-2.8.1. For Threshold 2, 11 additional Evaluation Groups are identified as potentially promising. All are continuous recycle systems with the exception of EG04 (once-through option with very high burnup fuel) and EG09 (limited recycle option).

This scenario differs from Scenario 1 only in the exclusion of Resource Utilization from the set of benefit criteria considered, so it is useful to compare the results of the two scenarios. When Resource Utilization is ignored (this scenario), only 1 of the once-through groups that were included in the promising set for Scenario 1 meet the threshold (EG04). In addition, several evaluation groups (EG21, EG22, EG25, EG31 and EG32) meet the threshold for this scenario but do not meet even Threshold 2 for Scenario 1. These five evaluation groups perform relatively poorly on the Resource Utilization Criterion (Appendix E, Figure E-6.5) and thus when that criterion is excluded in this scenario, they have relatively better performance.

Table F-2.8.1. List of Promising Evaluation Groups by Benefit, Scenario 8.

Threshold Type	**Evaluation Groups Within Threshold**
Highest Possible Benefit Utility (0.74)	EG23 EG24 EG30
Promising groups based on highest utility score	
Threshold (Benefit Utility = 0.66; 0.12 higher than EG01)	EG04 EG09 EG21 EG22 EG23 EG24 EG25 EG26 EG28 EG29 EG30 EG31 EG32 EG37
Promising groups based on lower thresholds established for individual Criteria (as applicable) and proportioned by the criteria tradeoff factors defined for the Scenario	
Color code	Once through / Limited recycle / Continuous recycle

Rankings considering both benefit and challenge

The ordered list of Evaluation Groups based on the benefit to challenge ratio is summarized in Table F-2.8.2. For the group identified by the threshold, EG21 has the highest ratio of incremental benefit to incremental challenge: Figure F-2.8.1 shows that that EG21 has relatively low challenge compared to the other Evaluation Groups that exceed this threshold, which is a significant contributor to the high ratio seen here.

Table F-2.8.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio for Different Utility Thresholds, Scenario 8.

Highest possible benefit utility via incremental benefit/challenge ratio*		Threshold 2 groups via incremental benefit/ challenge ratio*	
EG23	0.45	EG21	0.57
EG30	0.33	EG23	0.45
EG24	0.31	EG29	0.38
		EG31	0.35
		EG30	0.33
		EG04	0.32
		EG24	0.31
		EG37	0.27
		EG28	0.25
		EG09	0.23
		EG22	0.23
		EG26	0.23
		EG32	0.23
		EG25	0.20

* "Incremental" is defined by the difference in performance, on the utility scale representing benefit, and on the utility scale representing challenge, between an Evaluation Group and Basis of Comparison (EG01).

Sensitivity analyses

Figure F-2.8.2 illustrates the sensitivity analysis results considering the threshold defined above for identifying the potentially promising set.

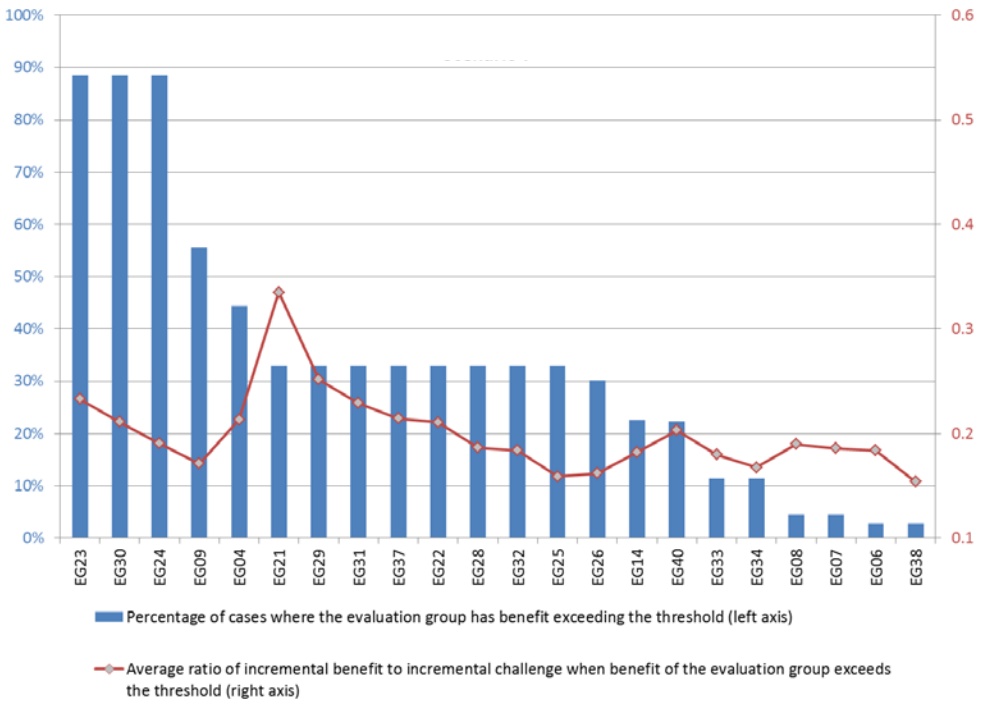


Figure F-2.8.2. Sensitivity Results for Scenario 8.

Figure F-2.8.2 shows that the three Evaluation Groups with the highest utility are most often in the promising set, with only one additional group (EG09) meeting the threshold in over 50% of the cases considered. All other Evaluation Groups listed above as meeting the threshold for the initial analysis are in the promising set between 20% and 50% of the time.

Summary - Promising Groups, Supporting R&D, Technical Requirements, and Insights

The potential supporting R&D items that are pertinent to the indicated promising options of this scenario are:

- 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.

F-2.9 Scenario 9 – Emphasis on Resource Utilization, Environmental Impact, and Safety Criteria

Definition of Scenario: Emphasize the importance of differences in three of the benefit criteria, excluding Nuclear Waste Management – to explore the impact of the correlation of Nuclear Waste Management and Resource Utilization criteria, by comparing the results of this scenario with that of Scenario 8 (Unlimited Resources).

Criteria tradeoff factors: This emphasis is implemented by assigning equal tradeoff factors of ~0.33 to each of the included criteria (Resource Utilization, Environmental Impact, and Safety) and a tradeoff factor of zero to the Nuclear Waste Management Criterion.

Results

The benefit and challenge results for this scenario for the 40 Evaluation Groups are presented graphically in Figure F-2.9.1.

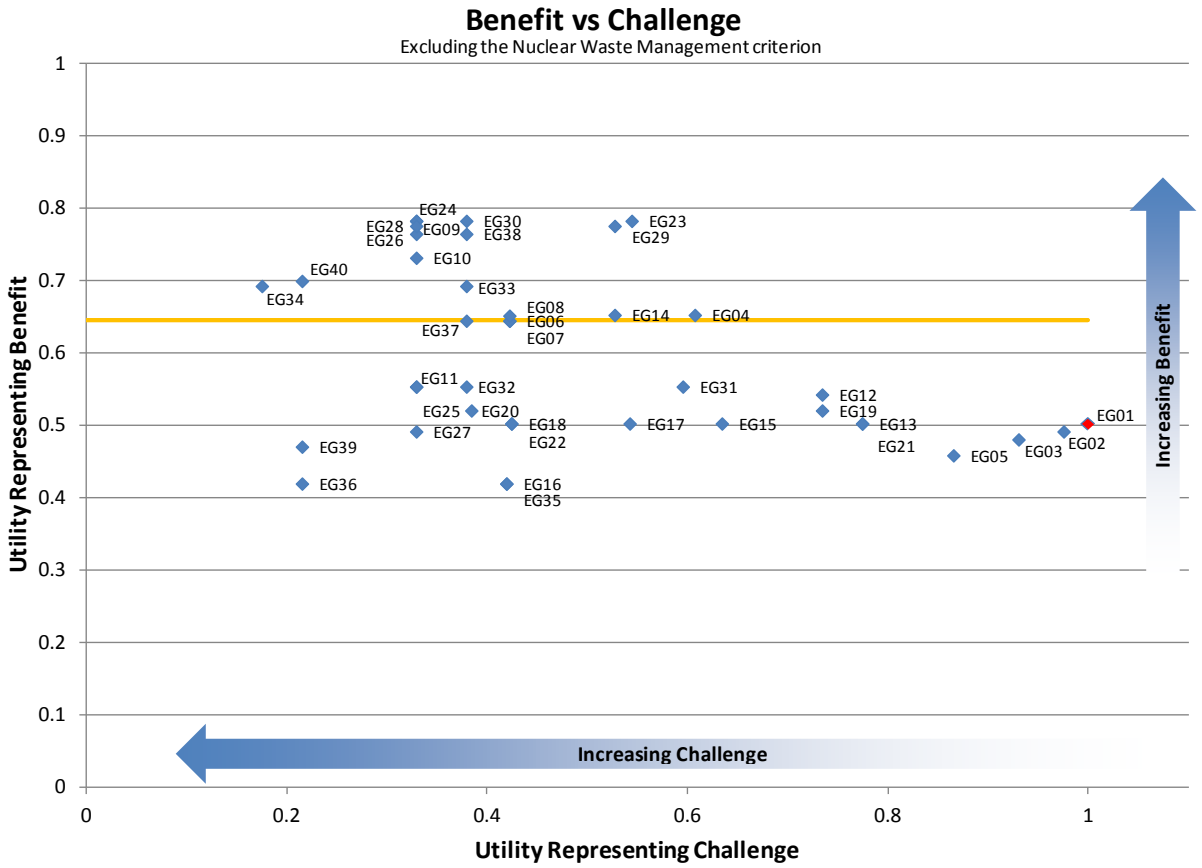


Figure F-2.9.1. Benefit versus Challenge Results for Scenario 9, Emphasis on Elimination of Nuclear Waste Management Criterion for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups based on benefit alone

The list of potentially promising Evaluation Groups that correspond to the benefit alone is show in Table F-2.9.1. In addition to the four evaluation groups that have the highest benefit utility for this scenario, a single threshold was defined as identifying a potentially promising set of evaluation groups, based on the single thresholds for each of the criteria included in this scenario.

Table F-2.9.1. List of Promising Evaluation Groups by Benefit, Scenario 9.

Threshold Type	**Evaluation Groups Within Threshold**
Highest Possible Benefit Utility (0.783)	EG09 EG23 EG24 EG30
Promising groups based on highest utility score	
Threshold 1 (Benefit utility = 0.645, 0.14 higher than EG01)	EG04 EG08 EG09 EG10 EG14 EG23 EG24 EG26 EG28 EG29 EG30 EG33 EG34 EG38 EG40
Promising groups based on thresholds established for individual Criteria and proportioned by the criteria tradeoff factors defined for the Scenario	
Color code	Once through / Limited recycle / Continuous recycle

EG09 (limited recycle of U/TRU to very high burnup in fast critical reactor without enrichment) shares the highest possible utility benefit along with EG23, EG24, and EG30 for this set of initial shape functions and metric tradeoff factors. The results for this scenario are similar to those of Scenario 3, which emphasizes the Resource Utilization Criterion. The results are also somewhat similar to those of Threshold 2 of Scenario 8, which emphasizes all benefit criteria except Resource Utilization, demonstrating the correlation between the Waste Management and Resource Utilization Criteria. There are exceptions to these similarities, however, in that Scenario 9 includes some Evaluation Groups with sub-critical reactors (EG08 and EG33) as promising. It should be noted that EG06 and EG07, also subcritical reactor options, were just below the threshold, as indicated in Figure 2.9.1. Additionally, this scenario identifies EG10 in the promising set, which is not included in Scenario 8. EG10 tends to consistently be identified in the promising set when the Resource Utilization Criterion is emphasized over that of Nuclear Waste Management, as it is in this scenario.

Rankings considering both benefit and challenge

The ordered list based on the benefit/challenge ratios are shown in Table F-2.9.2. The overall discussion of these results is similar to that for the rankings considering only benefit. The most apparent difference between the ranking of Scenario 9, emphasizing all benefit criteria except Nuclear Waste Management, and Scenario 8, emphasizing all benefit criteria except Resource Utilization, is the high ranking of EG21 for Scenario 8. EG21 and its counterpart EG22, met the threshold for Scenario 8 because the TRU are continuously recycled, eliminating them from waste disposal. Since Scenario 9 does not include Nuclear Waste Management Criterion, their benefit was less pronounced and thus excluded from the promising set that was established.

Table F-2.9.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio for Different Utility Thresholds, Scenario 9.

Highest possible utility via incremental benefit/challenge ratio*		Threshold 1 groups via incremental benefit/ challenge ratio*	
EG23	0.61	EG23	0.61
EG30	0.45	EG29	0.58
EG24	0.42	EG30	0.45
EG09	0.42	EG38	0.42
		EG09	0.42
		EG24	0.42
		EG28	0.41
		EG26	0.39
		EG04	0.38
		EG10	0.34
		EG14	0.32
		EG33	0.31
		EG08	0.26
		EG40	0.25
		EG34	0.23

* "Incremental" is defined by the difference in performance, on the utility scale representing benefit, and on the utility scale representing challenge, between an Evaluation Group and Basis of Comparison (EG01).

Sensitivity Analyses

Sensitivity analysis results for this scenario are shown in Figure F-2.9.2. This scenario has more robust performers than many of the previous scenarios, with eight evaluation groups meeting the threshold for all perspectives considered. This adds EG09, EG26, EG28, EG29, and EG38 to the three dominant Evaluation Groups (EG23, EG24, and EG30), which suggests that differences between the ranking of these five evaluation groups relative to the "top 3" is driven primarily, if not entirely, by differences in their performance on the Nuclear Waste Management Criterion. Other differences include relatively better performance of EG10, EG11, and EG12 than seen in other scenarios. These Evaluation Groups each offer benefits on Resource Utilization, but less benefit in the Nuclear Waste Management metrics.

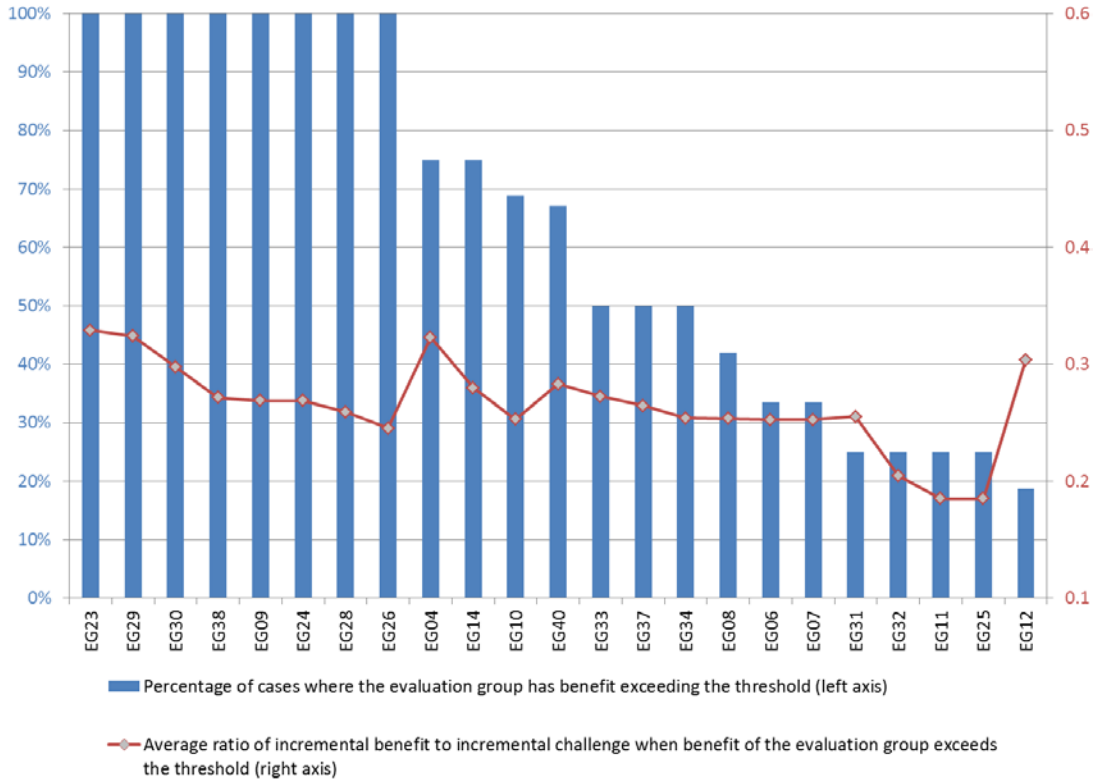


Figure F-2.9.2. Sensitivity Results for Scenario 9.

Summary – Most promising groups, Supporting R&D, Technical Requirements, and Insights

The promising groups identified for this scenario are similar to those identified for Scenario 1 with the inclusion of Resource Utilization strongly influencing the outcome. There is also some similarity in results, with noted exceptions, to those of Scenario 8, the Unlimited Resources Scenario. This similarity is due to the correlation between the Resource Utilization and Nuclear Waste Management Criteria. However, one can conclude that even though there is a high degree of correlation among Nuclear Waste Management and Resource Utilization Criteria, there are distinct differences in the results.

F-2.10 Scenario 10 – Emphasis on Nuclear Waste Management and Resource Utilization Criteria

Definition of the Scenario: This scenario emphasizes the importance of differences in Nuclear Waste Management and Resource Utilization Criteria over the two other benefit criteria (Environmental Impact and Safety Criteria,) in order to focus on the primary long-term and large-scale sustainability issues.

Criteria Tradeoff Factors: This emphasis is implemented by assigning a tradeoff factor of 0.5 to each of the included criteria and a tradeoff factor of zero to each of the other two criteria.

Results

The benefit and challenge results for this scenario for the 40 Evaluation Groups are presented graphically in Figure F-2.10.1.

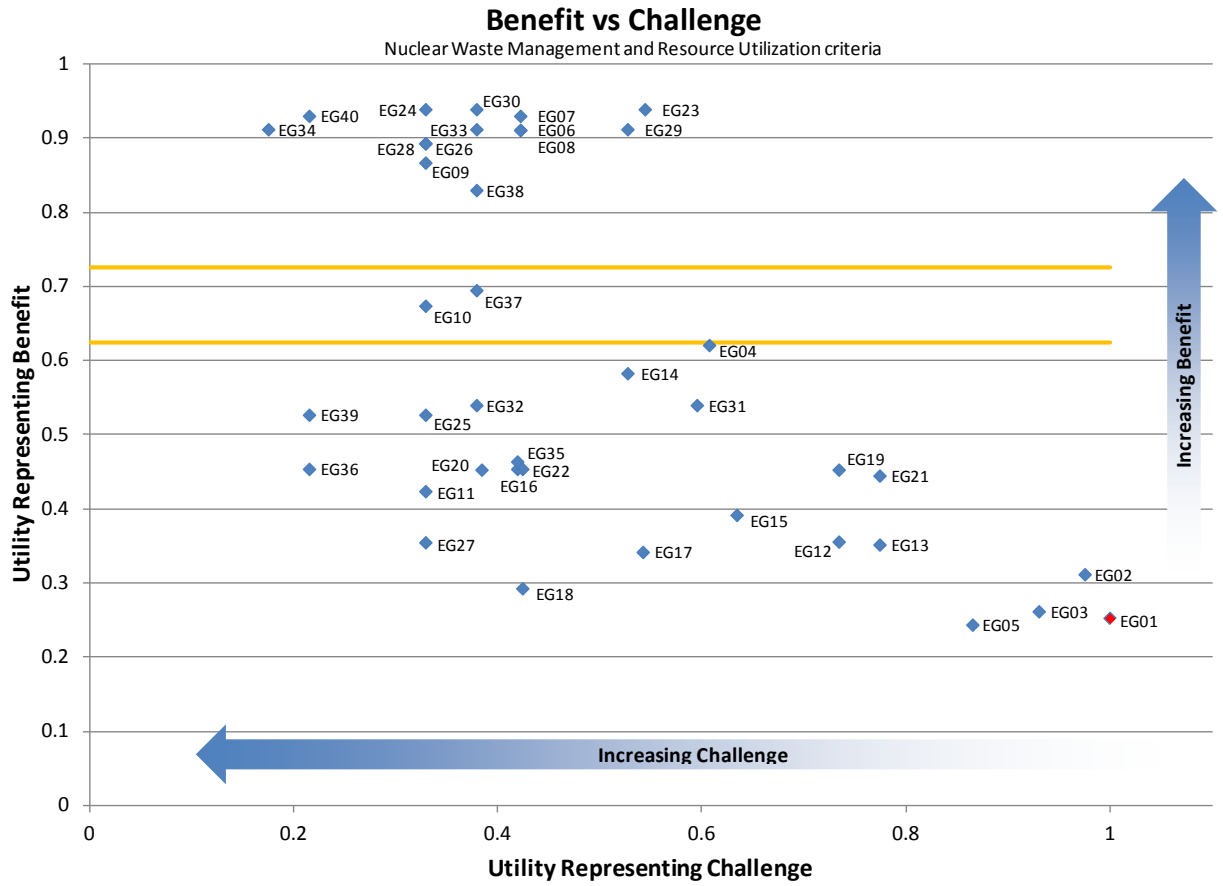


Figure F-2.10.1. Benefit versus Challenge Results for Scenario 8, Emphasize Nuclear Waste Management and Resource Utilization Criteria for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups based on benefit alone

The list of potentially promising Evaluation Groups that corresponds to benefit alone is shown in Table F-2.10.1. For this scenario, the highest utility value obtained by any Evaluation Group is 0.94, and three Evaluation Groups have this utility value: EG23, EG24, and EG30, the same three EGs involving the continuous recycle of Pu or TRU as were identified in most other scenarios.

For this scenario, two thresholds were defined as identifying potentially promising sets of Evaluation Groups, based on the two thresholds identified for the Nuclear Waste Management criterion and the

single threshold defined for the other benefit criteria. Threshold 1 was defined by a benefit utility of at least 0.72 (at least 0.47 higher than the Basis of Comparison), and Threshold 2 was defined by a benefit utility of at least 0.62 (0.37 higher than the Basis of Comparison).

Threshold 1 and 2 results for this scenario are nearly identical to those for Scenario 1. Exceptions are the inclusion of EG06 (once-through Th to very high burnup in thermal EDS) in the first threshold for this scenario and the exclusion of EG04 (once-through U to very high burnup in fast critical reactor without enrichment) from Threshold 2 for this scenario. EG04 was just under the threshold for this scenario, whereas for Scenario 1, it just made the threshold. The only other difference is the relative utility value representing benefit, because of the higher tradeoff factors for the Resource Utilization and Nuclear Waste Management Criteria. This outcome demonstrates the strong influence these two criteria have over the results when the four benefit criteria are considered.

Table F-2.10.1. List of Promising Evaluation Groups by Benefit, Scenario 10.

Threshold Type	**Evaluation Groups Within Threshold**
Highest Possible Benefit Utility (0.94)	EG23 EG24 EG30
Promising groups based on highest utility score	
Threshold 1 (Benefit utility = 0.72; 0.47 higher than EG01)	EG06 EG07 EG08 EG09 EG23 EG24 EG26 EG28 EG29 EG30 EG33 EG34 EG38 EG40
Promising groups based on upper thresholds established for individual Criteria and proportioned by the criteria tradeoff factors defined for the Scenario	
Threshold 2 (Benefit utility = 0.62; 0.37 higher than EG01)	EG06 EG07 EG08 EG09 EG10 EG23 EG24 EG26 EG28 EG29 EG30 EG33 EG34 EG37 EG38 EG40
Promising groups based on lower thresholds established for individual Criteria (as applicable) and proportioned by the criteria tradeoff factors defined for the Scenario	
Color code	Once through / Limited recycle / Continuous recycle

Rankings considering both benefit and challenge

The ordered list of Evaluation Groups based on the benefit to challenge ratio is summarized in Table F-2.10.2 for the thresholds of 0.725 (Threshold 1) and 0.623 (Threshold 2).

Table F-2.10.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio for Different Utility Thresholds, Scenario 10.

Highest possible utility via incremental benefit/challenge ratio*		Threshold 1 groups via incremental benefit/ challenge ratio*		Threshold 2 groups via incremental benefit/ challenge ratio*	
EG23	1.51	EG23	1.51	EG23	1.51
EG30	1.11	EG29	1.40	EG29	1.40
EG24	1.02	EG07	1.17	EG07	1.17
		EG06	1.14	EG06	1.14
		EG08	1.14	EG08	1.14
		EG30	1.11	EG30	1.11
		EG33	1.06	EG33	1.06
		EG24	1.02	EG24	1.02
		EG26	0.96	EG26	0.96
		EG28	0.96	EG28	0.96
		EG38	0.93	EG38	0.93

	EG09	0.92	EG09	0.92
	EG40	0.86	EG40	0.86
	EG34	0.80	EG34	0.80
			EG37	0.71
			EG10	0.63

* "Incremental" is defined by the difference in performance, on the utility scale representing benefit, and on the utility scale representing challenge, between an Evaluation Group and Basis of Comparison (EG01).

This consideration for the benefit-to-challenge ratio results in an ordering of groups in which EG23 and EG29 are clearly the leading ones. These are fuel cycle systems involving the continuous recycle of uranium and plutonium. They are followed by EG06, EG07, and EG08, which use EDS and very high burnup fuel.

Sensitivity analyses

Figures F-2.10.2(a-b) illustrate the sensitivity analysis results for this scenario, for each of the two thresholds that are based on the difference from the benefit utility of the Basis of Comparison (EG01). The 14 Evaluation Groups that meet the higher threshold value shown above are relatively robust to the various perspectives: exceeding the higher threshold value as or more often than any other Evaluation Groups and exceeding the lower threshold value for at least 75% of the perspectives considered. Of those Evaluation Groups meeting the second (lower) threshold for the initial analysis, only two, EG10 and EG37, do not exceed that threshold for a majority of perspectives. Finally, EG04 exceeds the higher threshold utility for a relatively small number of perspectives (~18% of all cases considered), but when it does it has a very high ratio of incremental benefit to challenge.

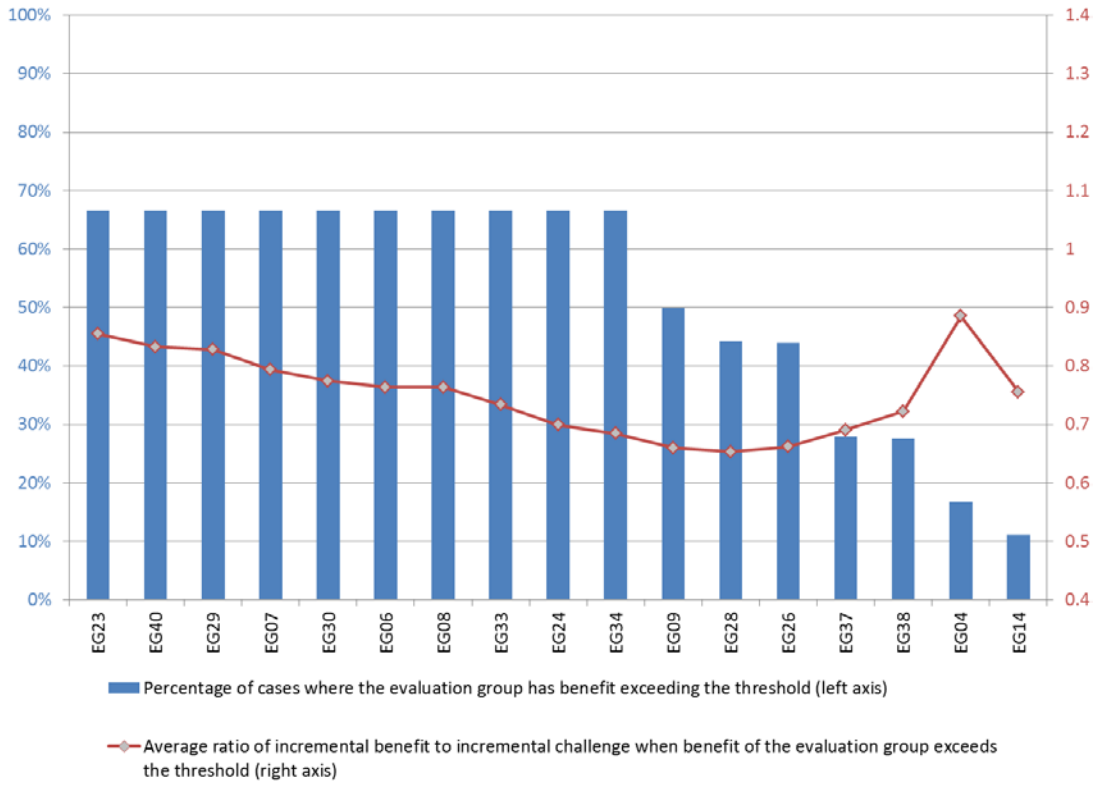


Figure F-2.10.2a. Sensitivity Results for Scenario 10, Higher Utility Threshold.

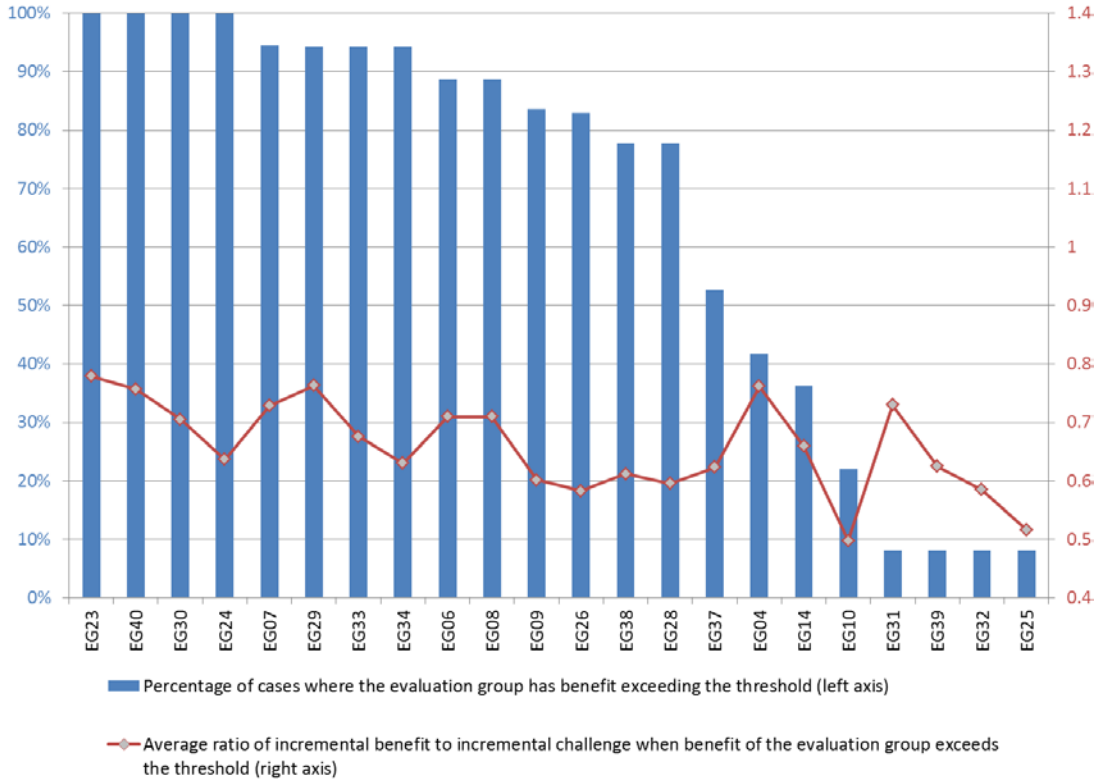


Figure F-2.10.2b. Sensitivity Results for Scenario 10, Second Utility Threshold.

Summary - Promising Groups, Supporting R&D, Technical Requirements, and Insights:

The potential supporting R&D items that are pertinent to the indicated promising options of this scenario are:

- 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.

F-2.11 Scenario 11 – Emphasis on Nuclear Waste Management and Safety Criteria

Definition of Scenario: Emphasize the importance of differences in the Nuclear Waste Management and Safety Criteria– to explore a cross-cutting focus on differing perspectives.

Criteria tradeoff factors: This emphasis is implemented by assigning equal tradeoff factors of 0.5 to each of the included criteria and a tradeoff factor of zero to each of two other benefit criteria (Environmental Impact and Resource Utilization criteria).

Results

The benefit and challenge results for this scenario for the 40 Evaluation Groups are presented graphically in Figure F-2.11.1

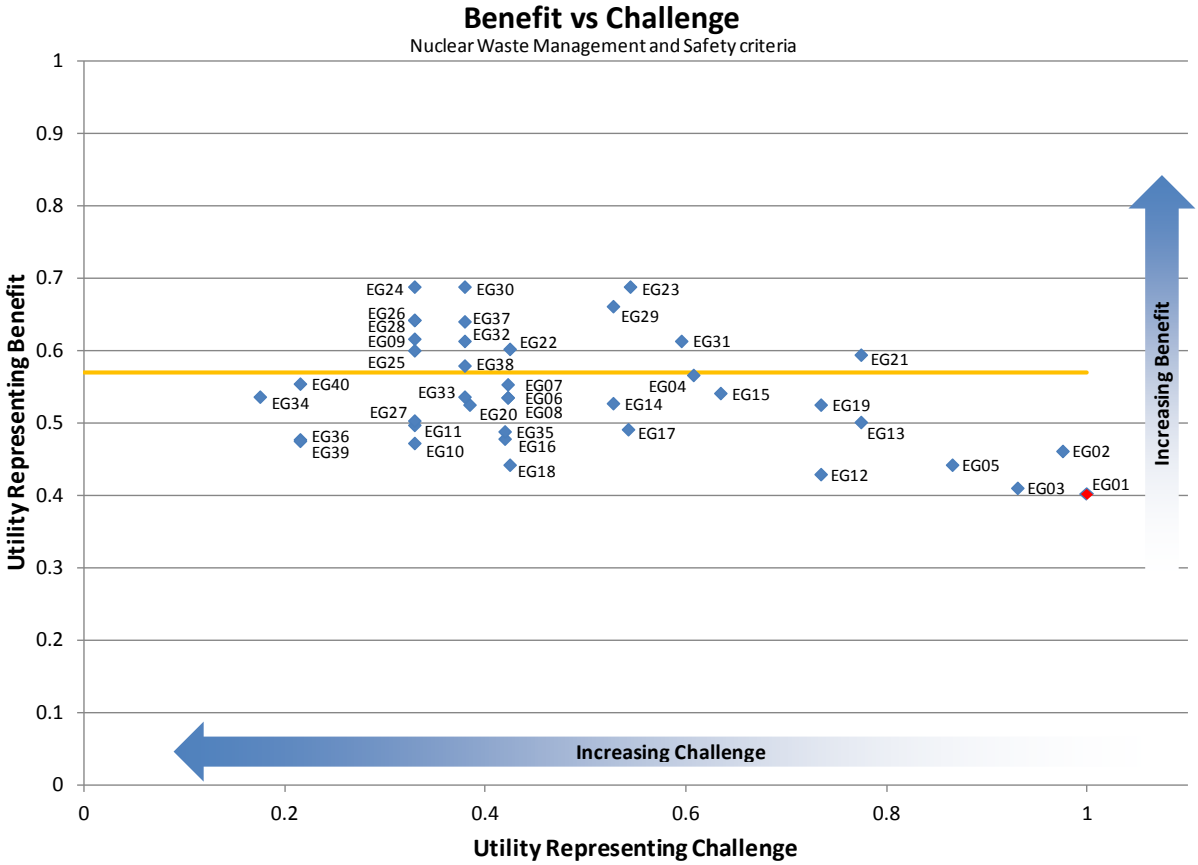


Figure F-2.11.1. Benefit versus Challenge Results for Scenario 11, Emphasis on the Nuclear Waste Management and Safety Criteria for the Initial Set of Shape Functions and Metric Tradeoff Factors.

Potentially promising Evaluation Groups based on benefit alone

The list of potentially promising Evaluation Groups that correspond to the benefit alone is show in Table F-2.11.1. The threshold for defining the potentially promising set is based on a combination of the thresholds for the individual criteria using the criteria trade-off factors. The results for this scenario are dominated by the results for Nuclear Waste Management, although the impact of the Safety Criterion can be seen. As a result the overall results for this scenario are similar to the criterion-level results for Nuclear Waste Management (Appendix E-1, Table E-1.5) except that the Evaluation Groups with sub-critical reactors (EG06, EG07, EG08, EG16, EG33, EG34, EG35, EG36, EG39, and EG40) are not identified as promising in this scenario. Those Evaluation Groups have a lower calculated benefit utility than the Basis of Comparison for the Safety Criterion. The Evaluation Groups with the highest utility value for this scenario are the same as those identified in most other scenarios. Those identified by the threshold include several continuous recycle options with enrichment (EG21, EG22, EG25, EG31, and EG32). This can be attributed, at least in part, to the fact that Resource Utilization is not considered in

this scenario, and the environmental impacts associated with enrichment and acquiring fuel resources are not considered.

Table F-2.11.1. List of Promising Evaluation Groups by Benefit, Scenario 11.

Threshold Type	**Evaluation Groups Within Threshold**
Highest Possible Benefit Utility (0.69)	EG23, EG24, EG30
Promising groups based on highest utility score	
Threshold 1 (Benefit utility = 0.57; 0.17 higher than EG01)	EG09, EG21, EG22, EG23, EG24, EG25, EG26, EG28, EG29, EG30, EG31, EG32, EG37, EG38
Promising groups based on thresholds established for individual Criteria and proportioned by the criteria tradeoff factors defined for the Scenario	
Color code	Once through / Limited recycle / Continuous recycle

Rankings considering both benefit and challenge

When considering benefit and challenge, the ordered list based on the benefit/challenge ratios for the identified promising options are shown in Table F-2.11.2. The overall discussion of these results is similar to that for the rankings considering only benefit. The overall impact the Nuclear Waste Management Criterion is to emphasize those Evaluation Groups that have high utility for that Criterion, while those that have low utility are also affected by the Safety Criterion.

Table F-2.11.2. Ordered Lists of Evaluation Groups by Incremental Benefit to Challenge Ratio for Different Utility Thresholds, Scenario 11.

Highest possible utility via incremental benefit/challenge ratio*		Threshold 1 groups via incremental benefit/ challenge ratio*	
EG23	0.63	EG21	0.85
EG30	0.46	EG23	0.63
EG24	0.43	EG29	0.55
		EG31	0.52
		EG30	0.46
		EG24	0.43
		EG37	0.38
		EG26	0.36
		EG28	0.36
		EG22	0.35
		EG32	0.34
		EG09	0.32
		EG25	0.30
		EG38	0.29

* “Incremental” is defined by the difference in performance, on the utility scale representing benefit, and on the utility scale representing challenge, between an Evaluation Group and Basis of Comparison (EG01).

Sensitivity Analyses

Sensitivity analysis results for this scenario are shown in Figure F-2.11.2.

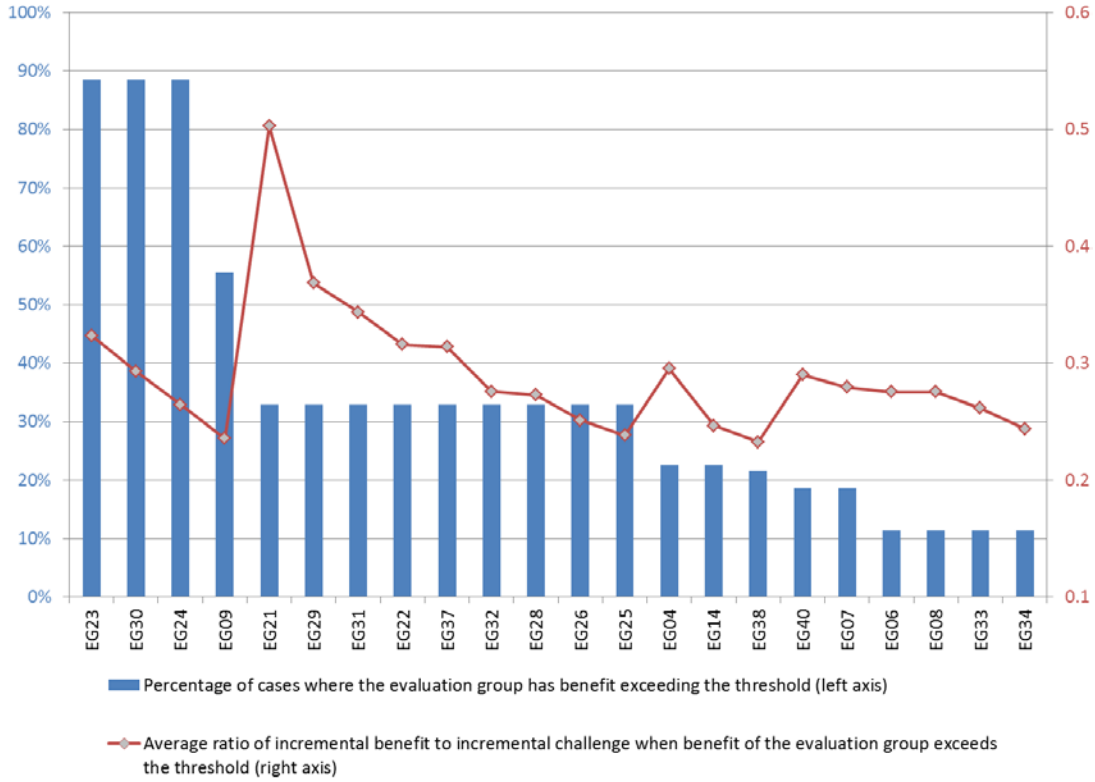


Figure F-2.11.2. Sensitivity Results for Scenario 11.

Unsurprisingly, these results are very similar the results with Nuclear Waste Management is considered alone, except that any Evaluation Group that poses higher safety challenge than EG01 does not make the threshold. As with several other scenarios there are numerous perspectives under which no Evaluation Groups exceed the threshold. In addition to the three Evaluation Groups that dominate others on the Nuclear Waste Management metrics (EG23, EG24, and EG30), only EG09 exceeds the threshold for more than half of the perspectives considered. EG21, which ranked highest in the initial analysis based on the ratio of incremental benefit to incremental cost discussed above, exceeds the threshold for only 33% of the cases considered, and similar performance can be seen for EG29, EG31, EG37, EG32, EG28, EG32, EG26, and EG25.

Summary – Most promising groups, Supporting R&D, Technical Requirements, and Insights

The promising groups identified for this scenario are similar to those identified for Scenario 1, with the inclusion Nuclear Waste Management strongly influencing the outcome. As a result, the consideration of the promising groups are similar to those identified in the Equal Tradeoff Factors scenario, with the observation that those Evaluation Groups with sub-critical systems achieve their primary benefit from being able to achieve high burnups are excluded.

F-3. Summary of Scenario-Level Sensitivity Analysis and Conclusions

The goal of this evaluation and screening was to identify promising fuel cycle options, defined as those that offer the potential for "significant improvement" over the currently deployed fuel cycle in the United States, to support decision-making about directions for DOE Nuclear Energy related research and development. As described throughout this report, different fuel cycle options might be considered "promising" by decision-makers or stakeholders who have different priorities or values. This study used a wide range of perspectives to represent this variability in decision-maker preferences, and the sensitivity analyses for each scenario identified Evaluation Groups that are robust to different perspectives: those that exceed the promise threshold for many of the perspectives considered. Section F-3.1 below summarizes the robust promising options for each scenario. Section F-3.2 describes a scenario-level sensitivity analysis aimed at identifying any Evaluation Groups that might be considered promising under an even wider range of perspectives than the individual criterion-level results and the 11 specific scenarios evaluated. Section F-3.3 provides conclusions, identifying the robust promising options.

F-3.1. Summary of results of single criterion and multiple-criteria scenarios

Figure F-3.1 shows the frequency with which each Evaluation Group meets at least one threshold under each of 11 scenarios. The first 4 columns show the single-criterion results, and the remaining columns show the results of Scenario 1 (equal tradeoff factors) and Scenarios 6-11 described above. As discussed previously, Scenarios 2-5, which "emphasize" the criteria one at a time do not provide additional insights over the results of the individual criteria-level results and Scenario 1, so they are not represented in this summary figure. This chart summarizes the sensitivity results for each case, where multiple perspectives on the relative value of the metrics within each criterion are considered: the "pie chart" in each cell indicates the percentage of perspectives under which the Evaluation Group meets the lower threshold for promise as defined for that scenario.

For example, EG23 (continuous recycle of U/Pu in fast critical reactors without enrichment) is promising when Nuclear Waste Management alone is considered under more than 75% of the perspectives and is considered promising as or more often than any other evaluation group for that criterion. It is also considered promising under all perspectives for the analyses focused exclusively on Environmental Impact and on Resource Utilization. When the multiple-criteria scenarios are considered, EG23 is considered promising under almost all perspectives for every scenario, and is included as or more often than any other Evaluation Group for all scenarios. EG24 (continuous recycle of U/TRU in fast critical reactors without enrichment) and EG30 (continuous recycle of U/TRU with both fast and thermal critical reactors without enrichment) have the same performance as EG23.

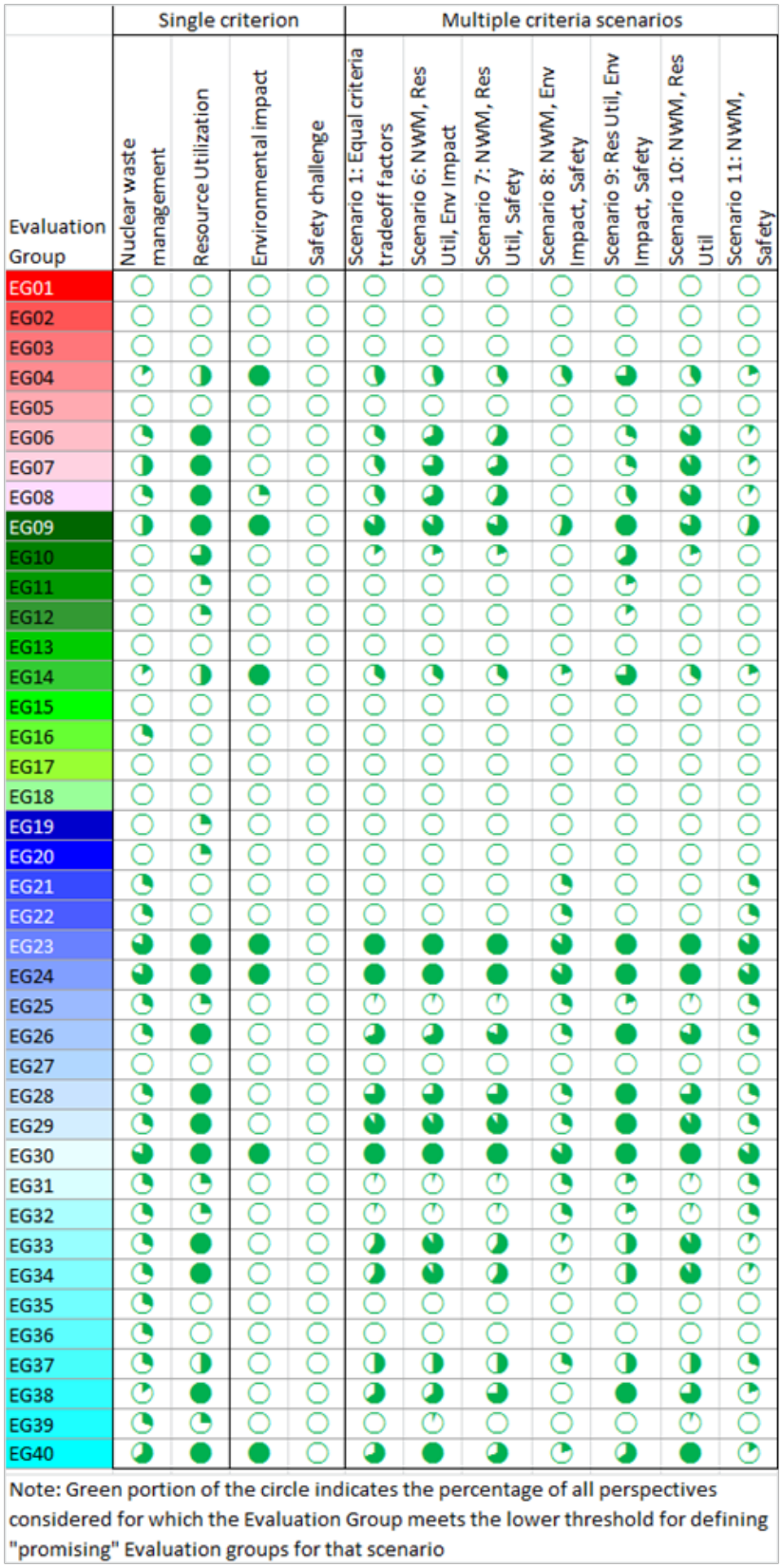


Figure F-3.1.1. Robustness of the Promising Evaluation Groups Identified for Single-criterion Analyses and Multiple Criteria Scenarios.

F-3.2. Scenario-level sensitivity analysis

Eleven specific scenarios were evaluated in detail, but clearly many other scenarios *could* be defined. To provide a further check on the robustness of the results of the study, the EST conducted a final set of sensitivity analyses, exploring a very wide range of potential scenarios through two simulation studies. The first simulation study used randomly generated criteria tradeoff factors (normalized to sum to 1), combined with random samples from the set of defined shape functions and metric tradeoff factors for each criterion. A million iterations of this simulation were run, and the benefit utility for each Evaluation Group was calculated. These results represent a (large) sample of any result that might be obtained considering the shape functions and metric tradeoff factors defined for this study, and any combination of criteria tradeoff factors for the four benefit criteria that were considered in the scenario analyses. While this approach will necessarily include sets of criteria tradeoff factors that represent very extreme views, Evaluation Groups that have high utility values under a large majority of these simulations, even for extreme views, are highly robust to different perspectives on the relative importance of changes across the criteria.

To summarize these results, Figure F-3.2.1 shows the range of benefit utility of the Evaluation Group relative to the benefit utility of the Basis of Comparison – roughly how much "better" or "worse" each evaluation group is than the Basis of Comparison. In the figure, Evaluation Groups are sorted by the mean difference. Several conclusions can be drawn from this analysis:

- The same three Evaluation Groups identified in the study for a variety of benefit criteria and scenarios as high performers can be characterized as consistently robust across an even wider range of perspectives; EG23, EG24, and EG30 always have higher utility value than the Basis of Comparison, and comparing across any fractile of the distribution their utility value is higher than all other Evaluation Groups.
- There are 11 Evaluation Groups that both have a high mean incremental utility over the Basis of Comparison (a mean incremental utility greater than 0.15) and *consistently* have a higher utility value than the Basis of Comparison (better in at least 95 percent of cases, as illustrated by their fifth percentile values lying above 0). These are: EG04, EG09, EG14, EG23, EG24, EG26, EG28, EG29, EG30, EG37, and EG38.
    - Eight of these also meet the highest utility threshold identified for Scenario 1 (with equal criteria tradeoff factors): EG09, EG23, EG24, EG26, EG28, EG29, EG30, and EG38. EG04 and EG37 meet the lower utility threshold.
- Six evaluation groups (EG06, EG07, EG08, EG33, EG34, and EG40) have a high mean incremental utility but also have the potential to have a lower benefit utility than the Basis of Comparison, as indicated by their 5^{th} percentile values lying below 0.
    - All of these evaluation groups met at least one of the threshold values for the initial analysis in Scenario 1, but EG06, EG07, and EG08 did not have robust performance in the Scenario 1 sensitivity analyses, meeting the threshold in fewer than half of the perspectives considered.
- Seven additional evaluation groups (EG13, EG15, EG21, EG22, EG25, EG31, EG32), are always better than EG01 in this simulation study, but have lower incremental utility overall than the 11 groups identified above.

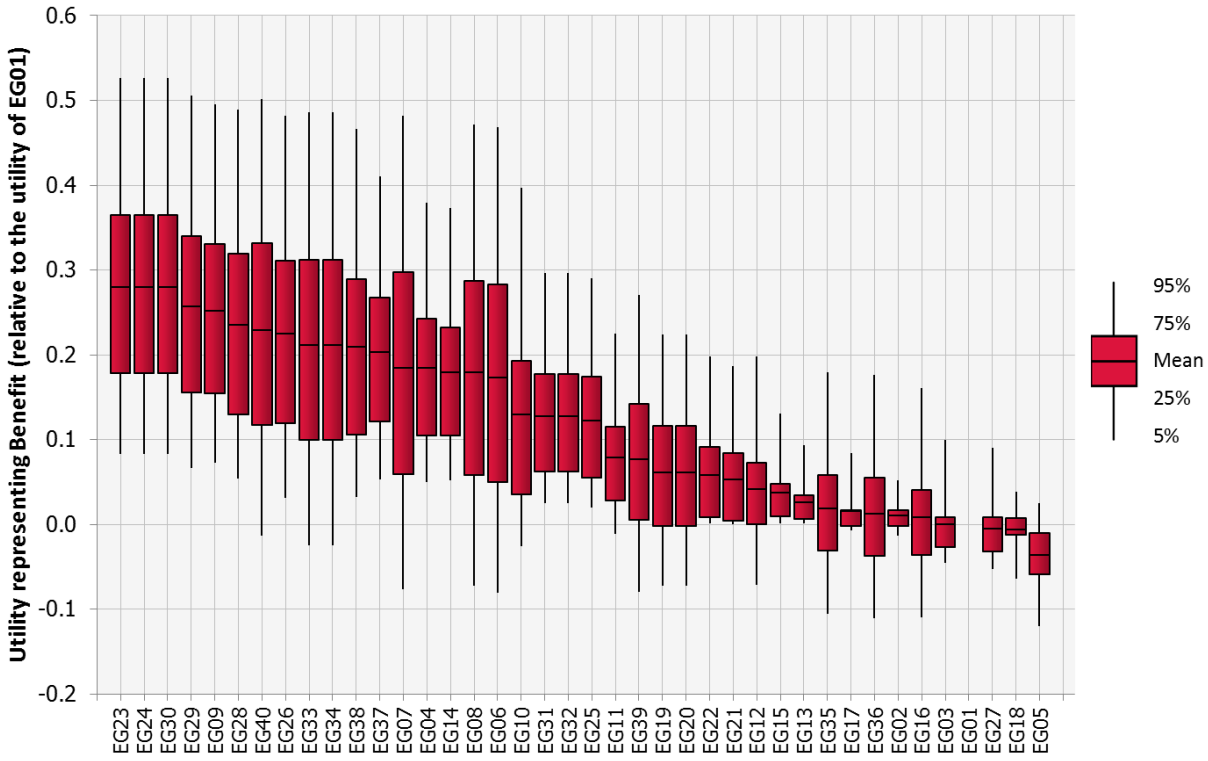


Figure F-3.2.1. Sensitivity Results Considering 1,000,000 Different Sets of Criteria Tradeoff Factors, Considering All Defined Sets of Shape Functions and Metric Tradeoff Factors.

- There are three to seven Evaluation Groups that would not likely be considered promising under any perspective. Three Evaluation Groups have mean incremental utility of less than 0 – meaning that on average they have lower utility than EG01. These are EG27, EG18, and EG05. An additional four Evaluation Groups have 95th percentile values that are less than 0.1 higher than the Basis of Comparison. These are EG03, EG02, EG13, EG17, and EG13. None of these Evaluation Groups were identified as potentially promising for any of the individual scenarios described above.
- Every Evaluation Group could be considered better than the Basis of Comparison, by at least a small amount for at least a few perspectives.

The final sensitivity analysis widened the range of perspectives considered even farther, varying both the metric tradeoff factors and the criteria tradeoff factors randomly. For this analysis, 10 simulations of 1,000,000 iterations each were run. The results are shown in Figure F-3.2.2 and are quite similar to the results above. Because of this similarity of results, this analysis helps support the overall conclusions from the scenario analyses as to which Evaluation Groups are the most robust performers.

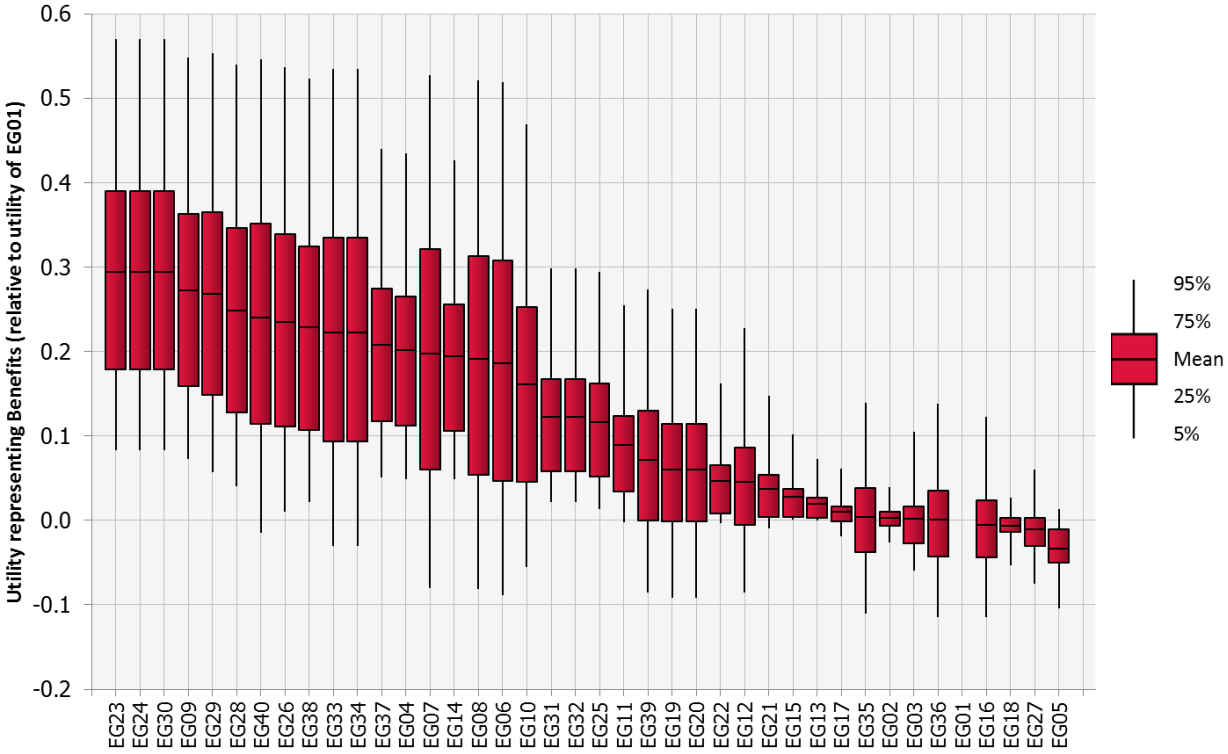


Figure F-3.2.2. Sensitivity Results Considering 10 Simulations of 1,000,000 Iterations with Different Sets of Criteria Tradeoff Factors and Metric Tradeoff Factors, Considering All Defined Sets of Shape Functions.

Figure F-3.2.3 illustrates these results in the same format used to show the sensitivity or robustness results for each scenario. Here an arbitrary threshold of an incremental benefit utility of 0.15 was chosen, based on observation of an apparent "step change" in the mean incremental utilities shown in Figure F-3.2.1 between EG06 and EG10. Figure F-3.2.3 show the percentage of simulation runs where each evaluation group exceeds this threshold, as well as the average incremental benefit to incremental cost ratio for those cases. Seventeen Evaluation Groups exceed this threshold for more than 50% of all perspectives. Two Evaluation Groups do not often exceed the threshold, but when they do, they offer relatively high incremental benefit to incremental challenge ratios: EG19 and EG12. The figure shows results only for evaluation groups that meet the threshold in at least five percent of the cases considered.

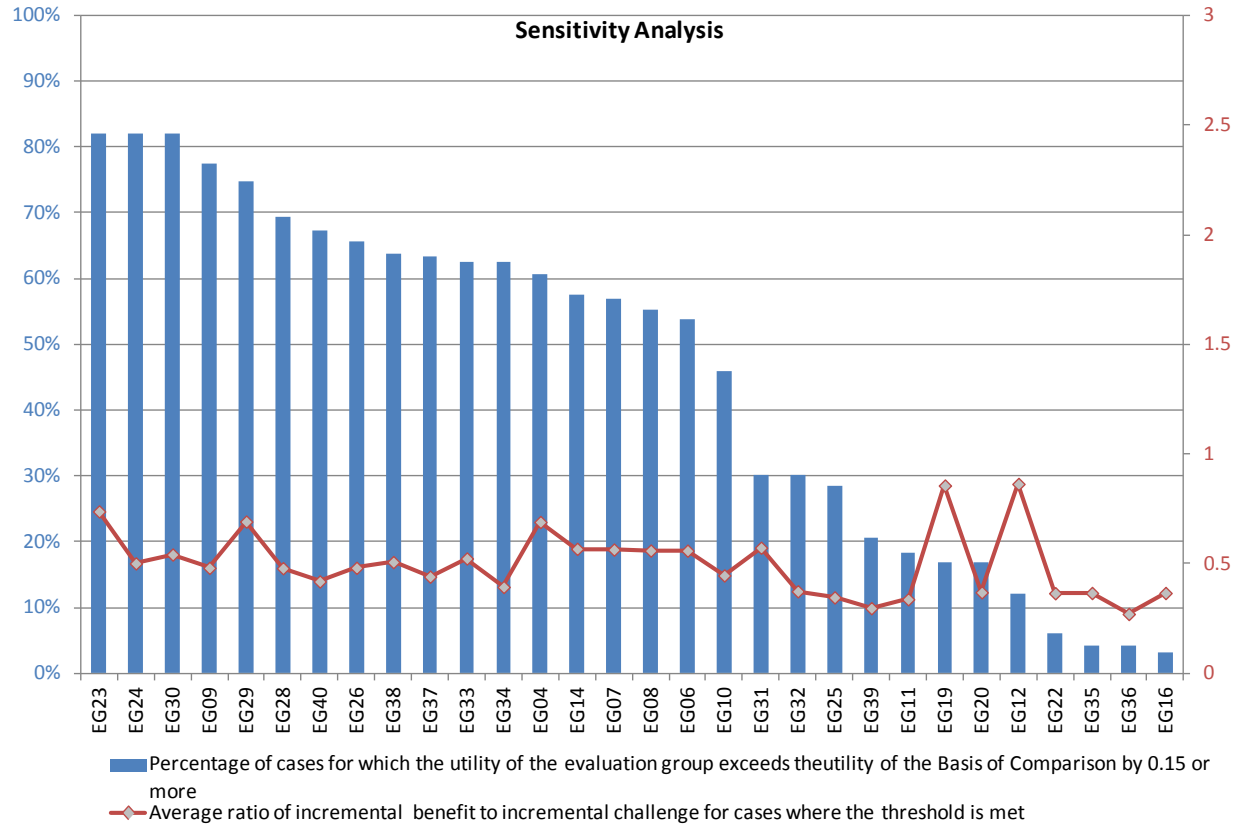


Figure F-3.2.3. Scenario-level Sensitivity Results: Percentage of Simulation Runs Where the Incremental Utility Exceeds a Threshold of 0.15, and the Ratio of Incremental Benefit to Incremental Challenge for those Evaluation Groups Exceeding the Threshold.

F-3.3. Conclusions: Promising Evaluation Groups Considering Multiple Criteria

The analyses presented in this Appendix reflect the results obtained for multiple Evaluation Criteria. As described in Section F-1.2, the approach for the sensitivity analyses is capable of identifying Evaluation Groups that may be promising for a wide variety of perspectives, informing on the "robustness" of the identification of the promising options. Based on the scenario analyses described above, and informed by the scenario-level sensitivity analyses, three Evaluation Groups were identified as the most promising, when benefit alone was considered:

- EG23 - Continuous recycle of U/Pu[a] 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

[a] Note: U= uranium; Pu = plutonium; TRU = transuranic elements, i.e., atomic number higher than uranium (Neptunium, Plutonium, Americium, Curium, .); Th=thorium

Of these three, EG23 appears to be less challenging to develop and implement. These three Evaluation Groups have the same metric data for four benefit criteria, and perform as well as, or better than, any other Evaluation Group for all benefit Criteria. For any perspective that places value on reduction in waste generation and efficient use of resources, they outperform all other Evaluation Groups.

These analyses also identified 8 additional Evaluation Groups were better than the Basis of Comparison for almost any possible scenario (better in at least 95 percent of cases, as illustrated by their fifth percentile values lying above 0), and have a mean incremental utility that is higher than the Basis of Comparison by 0.15 or more.

- 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
- 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
- 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

Finally, an additional 7 Evaluation Groups were identified that were better than the Basis of Comparison for most of the scenarios (but do perform worse than the Basis of Comparison under some perspectives)

- 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
- 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
- EG40 - Continuous recycle of ^{233}U/Th with new Th fuel in fast EDS and thermal critical reactors

Additional Insights from the Scenarios

As discussed in Section F-1.2, the approach of using a fixed incremental threshold to explore the robustness of the identification of promising options has the potential to miss identifying options that may be promising under a more limited set of scenarios. Recognizing this, Scenarios 1-15 were examined to identify any other potentially promising options.

Starting with Scenario 1, the equal weight scenario, Table F-2.1.1 shows all 17 of the Evaluation Groups listed here are above the lower threshold, as is EG10. Examining the Criteria level results to understand the source of the performance of EG10, it is clear that EG10 has a high utility for Resource Utilization but a relatively low utility for Nuclear Waste Management. This is observed for the scenarios as well, with EG10 being identified as potentially promising if efficient use of fuel resources is emphasized. For example, when Resource Utilization is emphasized (Scenarios 2, 9, and 13), EG10 has a utility above the threshold, with higher utility than EG04. On the other hand, when Nuclear Waste Management is emphasized (Scenario 3), the utility for EG10 is below the threshold. Based on these considerations,

EG10 is a candidate to be included in the group of potentially promising options for a limited number of perspectives, but for those perspectives, it performs very well. The possibility of adding EG10 to the list is supported by the results in Figs. F-3.2.1 where although the mean for EG10 was not sufficient to rise above the incremental threshold of 0.12, the 95% value is comparable to EG04 and EG14, and the 5% value is higher than for EG06, EG07, and EG08 (but lower than for EG04 and EG14, which accounts for the mean for EG10 being lower than for EG04 and EG14). Examining Fig. F-3.2.2, a similar behavior is observed. To recognize that overall, EG10 has lower utility than EG04 and EG14, but performs much better than EG04 and EG14 on Resource Utilization, EG10 was added to the list of Evaluation Groups that could be promising to avoid screening out this option.

Further examination of the Scenario results and Figs F-3.2.1 and F-3.2.2 did not identify any other Evaluation Groups.

Promising Fuel Cycles

Recognizing that organizing the promising Evaluation Groups into sets of similar potential benefit is somewhat arbitrary, the EST used the thresholds on Figure F-2.1.1 (Scenario 1, equal criteria tradeoff factors), and Figures F-3.2.2, and F-3.2.3 as guides to identify three sets, as follows:

Most Promising Fuel Cycles and Their R&D Needs

Among all options, three Evaluation Groups consistently provided the highest improvements compared to the current fuel cycle in the U.S., regardless of the perspective on the relative importance of the six benefit criteria.

- 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

When considering both benefit and challenge, another group can be considered that has slightly less improvement but lower challenge compared to EG24 and EG30:

- EG29 - Continuous recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors

Additional Potentially Promising Fuel Cycles and Their R&D Needs

The Study identified eleven additional *potentially promising Evaluation Groups* that provide somewhat lower beneficial improvements than the four discussed above:

- 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
- 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
- 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
- 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

Other Potentially Promising Fuel Cycles and Their R&D Needs

In addition to the Evaluation Groups listed above, a few additional lesser performing Evaluation Groups may be potentially promising depending on the relative importance of the underlying criteria and metrics:

- 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

If other scenarios that apply importance to Nuclear Waste Management and Resource Utilization were used, the most promising options would be much the same (although EG29 could move into a lower set), and there could be different organization of the other Evaluation Groups. However, for the purposes of informing DOE on most promising options and other potentially promising options, this organization appears to inform appropriately.