APPENDIX D

METRIC DATA

CONTENTS

FIGURES

TABLES

D. METRIC DATA

This appendix discusses the development of Metric Data for the Evaluation Metrics using the approaches described in Appendix C. Metric Data is provided in a "bin" format, i.e., the performance of an Evaluation Group is represented by placing the Evaluation Group in the appropriate bin with the range of the bin reflecting and encompassing the performance range for the best performing fuel cycle options within the Evaluation Group on each Evaluation Metric. Although the Study treats the identification of promising options as a "conditional" statement as described in the Main Report and Appendix A, DOE-NE requested that the EST provide an expert opinion on what constituted a significant improvement for each Evaluation Metric and Criterion. This information is provided in Appendix E, Section E-10 for all Criteria and Metrics.

Content and Structure of Appendix D:

Section D-1 presents background information applicable to all Evaluation Metrics. Subsequent subsections describe the development of Metric Data for all 40 Evaluation Groups, one metric at a time. The order of presentation below follows the order in which the metrics for the Criteria were introduced in Appendix C. In addition to describing the development of the Metric Data, in each subsection, one or more sets of potentially promising Evaluation Groups may be identified based on the potential for improvement. After all of the discussions of the metric data, there are several sections at the end of Appendix D that discuss more general fuel cycle issues such as processing of spent fuel and extended storage, aspects that can be applied to many or all fuel cycles.

D-1. Background Information on Metric Data

Development of Metric Data for the metrics informing on the Nuclear Waste Management, Environmental Impact, and Resource Utilization was supported by quantitative information about fuel cycle performance. For those Evaluation Metrics, quantitative data from an Analysis Example for each Evaluation Group was used to provide an initial indication of the performance of an Evaluation Group. As described in Appendix A, the Analysis Examples only specified a technology for irradiation of nuclear fuel, with all other parts of the fuel cycle being described at the functional level. However, as presented in Appendix B, the irradiation environment used the characteristics of typical examples, such as a PWR for a thermal reactor, that included performance parameters such as thermal efficiency for electricity production. To ensure that the Evaluation and Screening provided an unbiased view of the relative potential of fuel cycles, the mass flow information and similar quantitative data was renormalized so that all Analysis Examples used the same thermal efficiency. The renormalization is discussed as the first section in this Appendix as background information for all of the Evaluation Metrics.

After the renormalization, the resulting data was examined considering the Fuel Cycle Groups in each Evaluation Group to determine the appropriate bin for the Evaluation Group, reflecting the potential range of fuel cycle performance to provide an indication of the potential performance of the better fuel cycles within the Evaluation Group. This process of identifying the most appropriate bin for an Evaluation Group is also described for each Evaluation Metric, as needed, since not all Evaluation Metrics required any adjustment as a result of this process. This process is consistent with one goal of the Evaluation and Screening study, to ensure that all potentially promising fuel cycle options would be identified and that no potentially promising fuel cycle option would be inadvertently screened out by including an option in a lesser-performing Evaluation Group.

D-1.1 Renormalization of Mass Flow Data

The mass flow data of the 40 Analysis Examples for the Evaluation Groups were developed using assumptions for the thermal efficiencies of the reactor technologies selected for the different stages of the Analysis Examples. Due to the potential for different thermal efficiencies to bias the Evaluation and Screening results due to these choices, (i.e., thermal efficiency reflects the reactor choice and is not a functional characteristic of the irradiation part of the fuel cycle; the Evaluation and Screening is based on functional characteristics such as fast spectrum irradiation, not technology-specific characteristics such as a sodium-cooled fast reactor, as explained in Appendix A), it was necessary to renormalize the mass flow data using uniform thermal efficiency values: renormalization using thermal efficiency value of 33% for all the reactors in each Analysis Example. The uniform thermal efficiency of 33% was selected as being close to the average thermal efficiency of the current commercial PWRs. Analytical formulas were developed for this re-normalization to modify the mass and the power sharing between reactors in the different stages of the fuel cycle options from the values in the mass flow data tables provided for each Analysis Example in Appendix B-5.1.

The general forms of the formulas are:

$$F_k^n = \frac{\omega_k}{\sum_i \omega_i F_i^o} F_k^o, \tag{D-1.1.1}$$

$$M_k^n = \frac{1}{\sum_i \omega_i F_i^o} M_k^o, \tag{D-1.1.2}$$

where the superscripts of "*n*" and "*o*" indicate the new and original thermal efficiencies, respectively, and the subscript denotes the stage number, and

F_k^n = Power-sharing fraction of k-th stage with new thermal efficiency,
F_k^o = Power-sharing fraction of k-th stage with original thermal efficiency,
M_k^n = Mass data of k-th stage in Mass Flow Data table with new thermal efficiency,
M_k^o = Mass data of k-th stage in Mass Flow Data table with original thermal efficiency,
ω_k = New to original thermal efficiency ratio of stage k (= η_k^n / η_k^o).

It is noted that the renormalization of the mass data for the externally-driven systems (EDS) had to be handled differently because a significant fraction of the power generated by those systems may be used to support the external source of neutrons, e.g., the accelerator in an ADS. For instance, the Analysis Example for EG07 is a once-through fuel cycle in which natural uranium is irradiated in a sub-critical system. The thermal power of the Analysis Example was assumed to be 1,000 MWt and the electricity used to support the EDS components (accelerator for this Analysis Example) was 123.0 MWe. For the plant thermal efficiency of 40%, the available electricity to the grid was 277 MWe. Thus, the effective thermal efficiency of the Analysis Example was calculated as 27.7%. If the plant thermal efficiency of the ADS had been 33%, however, then the effective thermal efficiency would have been 20.7%. The ratio of these two efficiencies 1.34 (27.7/20.7) is the factor by which the calculated mass values in the mass flow table have to be corrected. On the other hand, for EG02 this factor is just 50/33 = 1.52 (which is the ratio of the thermal efficiency used in the calculation for the mass flow data to the 33% specified for comparison on a uniform basis).

Normalized power sharing fractions and mass normalization factors are provided in Table D-1.1.

Table D-1.1. Power-sharing Fractions and Mass Renormalization Factors.

Thermal efficiency variation	Values in Mass Flow Data Table						Renormalization using thermal efficiency of 33%			
	Thermal efficiency, %			Power sharing fraction, %			Power sharing fraction, %			Mass renormalization factor
Stage	1	2	3	1	2	3	1	2	3	
EG01	33.0			100.0			100.0			1.00
EG02	50.0			100.0			100.0			1.52
EG03	33.0			100.0			100.0			1.00
EG04	40.0			100.0			100.0			1.21
EG05	50.0			100.0			100.0			1.52
EG06	36.4			100.0			100.0			1.46
EG07	27.7			100.0			100.0			1.34
EG08	33.3			100.0			100.0			1.43
EG09	40.0			100.0			100.0			1.21
EG10	44.4			100.0			100.0			1.35
EG11	40.0			100.0			100.0			1.21
EG12	33.0	33.0		76.1	23.9		76.1	23.9		1.00
EG13	33.3	33.3		90.2	9.8		90.2	9.8		1.01
EG14	40.0	33.0		70.6	29.4		66.5	33.5		1.14
EG15	33.0	40.0		88.1	11.9		90.0	10.0		1.02
EG16	33.0	29.9		92.6	7.4		94.2	5.8		1.02
EG17	33.0	33.0		90.5	9.5		90.5	9.5		1.00
EG18	33.0	33.0		68.7	31.3		68.7	31.3		1.00
EG19	33.0			100.0			100.0			1.00
EG20	33.0			100.0			100.0			1.00
EG21	33.3			100.0			100.0			1.01
EG22	33.3			100.0			100.0			1.01
EG23	40.0			100.0			100.0			1.21
EG24	40.0			100.0			100.0			1.21
EG25	33.0			100.0			100.0			1.00
EG26	44.4			100.0			100.0			1.35
EG27	40.0			100.0			100.0			1.21
EG28	40.0			100.0			100.0			1.21
EG29	40.0	33.0		61.1	38.9		56.4	43.6		1.12
EG30	40.0	33.0		87.0	13.0		84.7	15.3		1.18
EG31	33.0	40.0		68.2	31.8		72.2	27.8		1.06
EG32	33.0	40.0		63.4	36.6		67.8	32.2		1.07
EG33	34.5	33.0		83.7	16.3		80.4	19.6		1.20
EG34	34.8	33.0		80.0	20.0		76.2	23.8		1.19
EG35	33.0	31.1		84.7	15.3		87.7	12.3		1.04
EG36	33.3	35.0		93.5	6.5		94.7	5.3		1.02
EG37	33.3	40.0	32.4	11.9	50.1	38.0	12.8	45.0	42.2	1.09
EG38	40.0	33.0		85.5	14.5		83.0	17.0		1.18
EG39	33.0	33.0	26.0	69.6	24.3	6.0	70.8	24.8	4.4	1.02
EG40	23.6	33.0		20.5	79.5		15.4	84.6		1.06

These renormalization factors are used for multiplying the mass values calculated from the mass flow data tables in Appendix B-5.1 to derive the normalized masses at 33% efficiency for each Analysis Example. The associated renormalized power sharing is also applied for metric calculations.

D-2. Metric Data

The following sections present the development of the Metric Data, one metric at a time, in the order in which the metrics for the Criteria were discussed in Appendix C.

D-2.1 Mass of SNF+HLW Disposed per Energy Generated

Calculation of Metric Information

The mass of Spent Nuclear Fuel and High Level Waste (SNF+HLW) is defined as the initial heavy metal mass minus any masses recycled in the fuel cycle option or the heavy metal masses (such as depleted uranium (DU), recovered uranium (RU), and recovered thorium (RTh)). Based on this definition, the mass of SNF+HLW includes the discharged fuel (DF) that is directly disposed, non-recycled heavy metals (except for DU, RU, and RTh), non-recycled fission products, and process losses.

The SNF+HLW mass metric information has been calculated from information in the "Mass Flow Data" tables presented in Appendix B-5.1 for the 40 Analysis Examples used to inform on the 40 Evaluation Groups in this Evaluation and Screening study. Figure D-2.1.1 and Table D-2.1.1 show the "Material Flow Diagram" and "Mass Flow Data" of the Analysis Example for Evaluation Group EG13, which is a two-stage limited recycle fuel cycle option. This information is provided to illustrate how the mass of SNF+HLW disposed per energy generated is derived from the mass flow data.

The first stage of EG13 contains Pressurized Water Reactors (PWRs) utilizing low-enriched uranium (LEU) nuclear fuel with average discharge burnup of 50 GWd/t. The second stage, also containing PWR technology, involves the reuse of plutonium and uranium recovered from the used nuclear fuel (discharged fuel, DF) of the first stage. The PWR in the second stage is similar to that in the first stage, and its fuel average discharge burnup is 50 GWd/t.

The mass data in Table D-2.1.1 were per 100 GWe-yr for an entire fleet, while the corresponding values in Figure D-2.1.1 were per unit GWe-yr because the Evaluation and Screening metrics are specified in the unit of energy generation (t/GWe-yr); the mass of SNF+HLW disposed per unit electricity generation (t/GWe-yr) at each stage are denoted by numbers in bold-red font in the figure. The signs (-) and (+) in Table D-2.1.1 indicate the input and output from each technology category, respectively.

For Stage 1 of the Analysis Example, there are two HLW (as defined in this report) streams: the material losses from reprocessing/separations, and the materials destined for disposal as waste, indicated by fission products (FP), and minor actinides (MA) disposed in HLW from reprocessing in this example. This stream does not include any of the excess RU.

The loss row of Table D-2.1.1 shows that the material loss from reprocessing/separations (Rep/Sep) going to the HLW stream is 0.197 t/GWe-yr. The row containing "MA" under the "Products from Rep/Sep technology" contains the amount of minor actinides discharged into the HLW stream and is 0.025 t/GWe-yr. The amount of fission products going into the HLW stream is taken from the row "FP" under Products from Rep/Sep technology" and is 1.019 t/GWe-yr (makes the HLW total to be 1.044 t/GWe-yr). The total of these three items is: 0.197 + 0.025 +1.019 = 1.241 t/GWe-yr.

There is no SNF disposed from the first stage because the discharged fuel (DF) is entirely recycled, while the DF mass in Stage 2 is considered as SNF. The value of the discharged SNF mass from Stage 2 is obtained from the row "DF" under "Products from fuel and NPPT technology" of Table D-2.1.1 and is 2.153 t/GWe-yr. Based on this data, the overall mass of SNF+HLW disposed per energy generated = 2.153 + 1.241 = 3.394 t/GWe-yr. Finally, the SNF+HLW mass data was additionally normalized to account for the fact that this Evaluation and Screening is being done with uniform thermal efficiency of 33%. The data from Table D-1.1 for EG13 (i.e., 1.01, but actually 1.0091) is consequently used to normalize mass of SNF+HLW to obtain 1.0091*3.394 = 3.42 t/GWe-yr.

Using similar calculations, the mass of SNF+HLW disposed per energy generated for each of the other Analysis Examples for the 40 Evaluation Groups can be obtained from the “Mass Flow Data” tables of Analysis Examples (see Appendix B-5.1) and using the mass normalization factor from Table D-1.1.

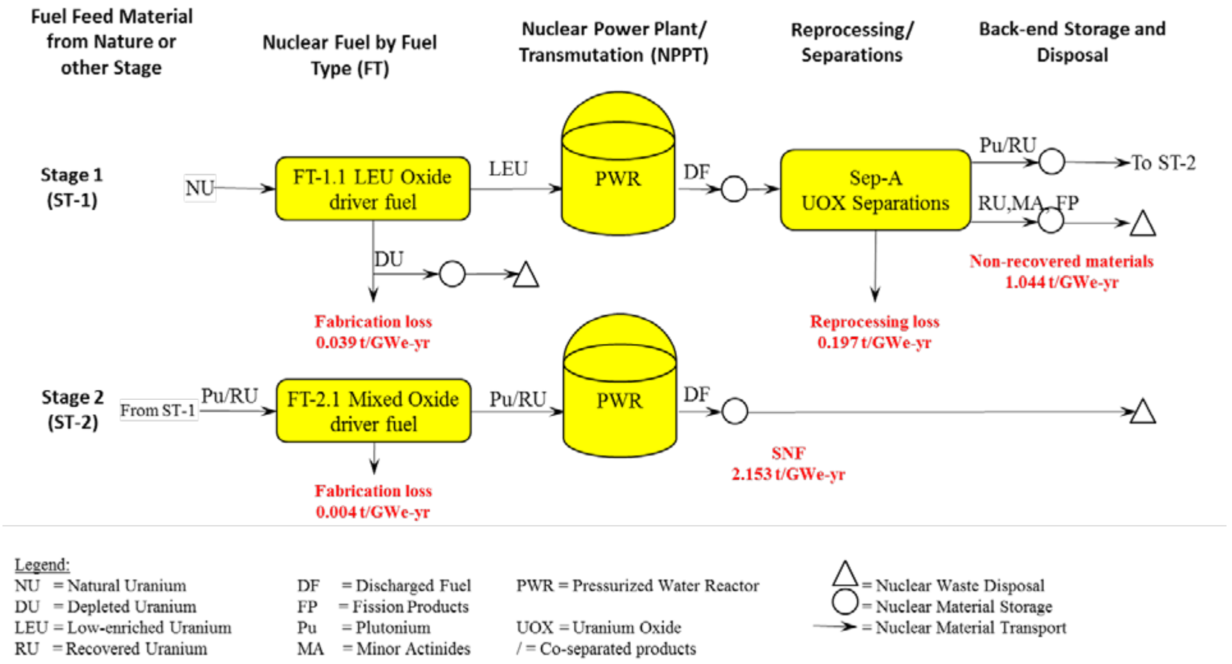


Figure D-2.1.1. Material Flow Diagram of Analysis Example for EG13.

Table D-2.1.1. Mass Flow Data of Analysis Example for EG13.

Stage		1			2			Sum
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		90.2			9.8			100.0
Feed or product of nuclear materials (tons per100 GWe-yr)[a]								
Natural resource	NU	-16,961.9						-16,961.9
	Th							-
Products from fuel or NPPT technology	DU	+14,983.3						+14,983.3
	U	+1,974.7	-1,974.7		+ 192.2	-192.2		0.0
	Pu				+ 23.1	-23.1		0.0
	DF		+1,974.7	-1,974.7		+215.3		+215.3
Products from Rep/Sep technology	RU			+1,827.4	-192.6			+1,634.9
	Pu			+23.1	-23.1			0.0
	MA			+2.5				+2.5
	FP			+ 101.9				+101.9
Loss		+3.9	0.0	+19.7	+0.4			+24.1

a) Mass flow in metric ton was developed to produce 100 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

The mass of SNF+HLW disposed per energy generated for all the 40 Analysis Examples for the Evaluation Groups are plotted in Figure D-2.1.2 for the 40 Evaluation Groups. The SNF+HLW mass varies from 1.25 t/GWe-yr to 147.57 t/GWe-yr. Figure D-2.1.2 shows that in general (but with a few exceptions), the mass of SNF+HLW disposed per energy generated decreases from the once-through fuel cycle options to those of continuous recycle fuel cycle options. The spent nuclear fuel (SNF) is the dominant contribution to the SNF+HLW mass for the once-through fuel cycle options, and the SNF mass is zero for the continuous recycle options. For the once-through fuel cycle options, the SNF mass is inversely proportional to the average discharge burnup. Thus, the once-through fuel cycle Analysis Example using Heavy Water Reactors (HWRs), which represents EG03, has the highest SNF+HLW mass because the discharge burnup from the HWRs is smallest amongst the 40 Analysis Examples. The relatively low SNF+HLW mass for the once-through strategy EG08 is due to the fact that the associated Analysis Example utilized only natural uranium as fuel and that fuel has a very high burnup (~75%).

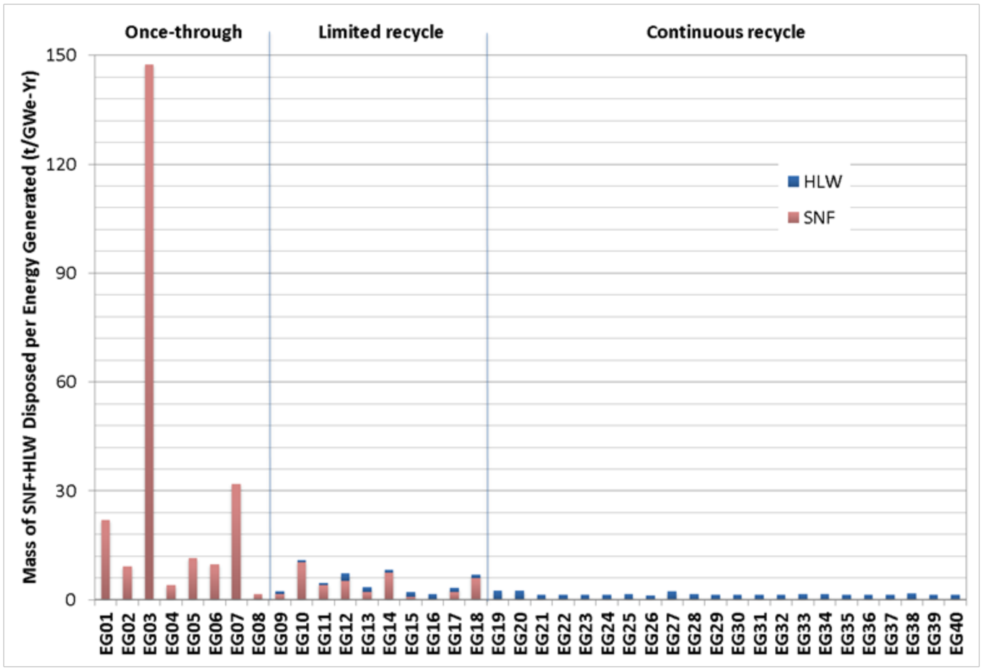


Figure D-2.1.2. Calculated Mass of SNF+HLW Disposed per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

The total SNF+HLW masses are comparable for the continuous recycle options, which consist of fission products (FPs), other waste products and material losses from used fuel reprocessing. Generally, the FP mass is comparable in all forty Analysis Examples because about the same mass of heavy metal is destroyed (or transformed to fission products) by fission to generate the same amount of electricity. The minor difference is due to the different thermal efficiencies and the corrections for externally-driven systems that are necessary because a portion of their fission energy is used for driving auxiliary systems (e.g. the accelerator in the ADS). Thus, the material losses from reprocessing govern the minimum bounding value of the SNF+HLW mass for the continuous recycle options. Due to the low loss fraction assumed for the MSRs, the Analysis Example for EG26 has the lowest SNF+HLW mass value.

Development of Metric Data

The 40 Analysis Examples provide an initial indication of the performance of the Evaluation Groups. Since an Evaluation Group encompasses multiple fuel cycle options in addition to the Analysis Example for the group, it is realized that the metric information calculated for the Evaluation Group could show some variability. Rather than rely on the single quantitative estimate for one Analysis Example to represent the Evaluation Group, it was considered that binning the metric information derived from each Analysis Example would better inform on the Evaluation Groups. In the following, the metric information calculated, the approach for binning, and for re-binning some evaluations groups are discussed.

Figure D-2.1.3 shows the Evaluation Groups ordered by the mass of SNF+HLW disposed per energy generated for each Analysis Example. Bins for the metric data were defined to recognize the variability in the mass of SNF+HLW across the different fuel cycle options included in an Evaluation Group, and in consideration of the following factors:

- The calculated mass of SNF+HLW disposed per energy generated varies by two orders of magnitude over the 40 Analysis Examples for the Evaluation Groups.
- Bins should recognize fuel cycles (once-through, limited and continuous recycle) and the magnitude of change of the metric over the 40 Evaluation Groups.
- The highest performing bin was defined by an upper boundary at ~1.65 t/GWe-yr. This is similar to the amount of HLW mass arising if the LWR SNF from the Basis of Comparison (EG01) was processed (see sensitivity study in this Appendix, Section D-3).

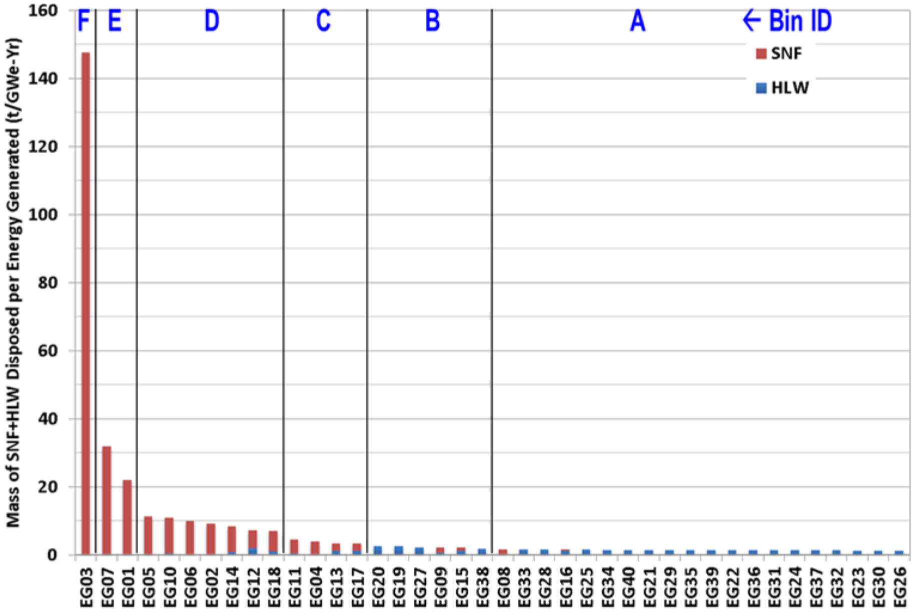


Figure D-2.1.3. Calculated Mass of SNF+HLW Disposed per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Decreasing Mass Information.

The bins that were determined for the mass of SNF+HLW metric, ranging from A (the highest performance bin) to F (the lowest performance bin), are presented in Table D-2.1.2.

Table D-2.1.3 lists the data for the Analysis Example by Evaluation Group number, the original bin corresponding to the Analysis Example data in the third column. For a few Evaluation Groups, the calculated mass of SNF+HLW disposed per Energy Generated for the Analysis Example was not considered representative of the overall performance of that Evaluation Group, and a decision was made to reassign those Evaluation Groups to different bins. The fourth and fifth columns of Table D-2.1.3 are the final metric data and explanations for changes from the initial binning. For example, the Evaluation Group EG07 was re-binned based on the realization that it would have given similar metric data results as EG08 if an FFH instead of ADS had been used with similar modeling assumptions in the Analysis Example and thus EG07 was placed in the same bin as EG08. Similarly, EG06 was re-binned in the same group as EG08, because even though it uses the same externally driven system, the assumptions for the burnup of EG06 were more conservative than that for EG08.

Table D-2.1.2. Metric Bins for Mass of SNF+HLW Disposed per Energy Generated.

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

Table D-2.1.3. Metric Data for Mass of SNF+HLW Disposed per Energy Generated.

EG	Calculated Mass (t/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG01	21.92	E	E	
EG02	9.22	D	D	
EG03	147.57	F	F	
EG04	3.99	C	C	
EG05	11.41	D	D	
EG06	9.86	D	A	EG06 would have given similar metric data result as EG08 if similar modeling assumptions had been used in its Analysis Example.
EG07	31.97	E	A	EG07 would have given similar metric data result as EG08 if an FFH instead of ADS and similar modeling assumptions had been used in its Analysis Example.
EG08	1.62	A	A	
EG09	2.24	B	B	
EG10	10.84	D	D	
EG11	4.54	C	C	
EG12	7.27	D	D	
EG13	3.42	C	C	
EG14	8.34	D	D	
EG15	2.11	B	B	
EG16	1.52	A	A	
EG17	3.37	C	C	
EG18	6.95	D	D	
EG19	2.59	B	B	

EG	Calculated Mass (t/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG20	2.61	B	B	
EG21	1.46	A	A	
EG22	1.39	A	A	
EG23	1.31	A	A	
EG24	1.34	A	A	
EG25	1.51	A	A	
EG26	1.25	A	A	
EG27	2.25	B	B	
EG28	1.58	A	A	
EG29	1.45	A	A	
EG30	1.30	A	A	
EG31	1.37	A	A	
EG32	1.32	A	A	
EG33	1.59	A	A	
EG34	1.50	A	A	
EG35	1.42	A	A	
EG36	1.39	A	A	
EG37	1.33	A	A	
EG38	1.79	B	B	
EG39	1.40	A	A	
EG40	1.47	A	A	

*The light blue background is used to denote Evaluation Groups with Analysis Examples using Th/U fuel; the light purple background denotes Evaluation Groups with Th-only fuel, and the white background denotes Evaluation Groups with U-only fuel.

The final Metric Data for the 40 Evaluation Groups are plotted on Figure D-2.1.4 (note that the same data is provided as the fourth column of Table D-2.1.3) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

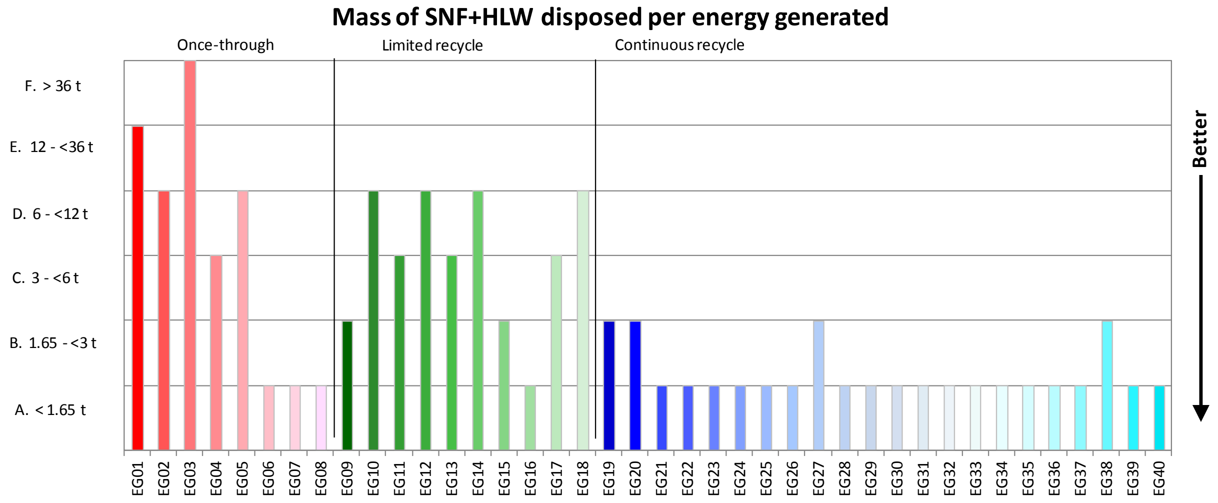


Figure D-2.1.4. Metric Data for Mass of SNF+HLW Disposed per Energy Generated for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups for Reducing the Mass of SNF+HLW

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

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

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

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

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

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

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

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

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

Comparing bin mid-points, bin C provides a factor of 5 reduction in mass of SNF+HLW relative to bin E.

The Analysis Example for EG04 is a fast-spectrum system in which only depleted uranium is used as input fuel feed material in the full-cycle equilibrium state. The Evaluation Groups EG11, EG13, and EG17 involve limited recycle options in which spent fuel is finally disposed.

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

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

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

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

Supporting R&D and Insights

Based on the identified Evaluation Groups above, arising from the conditional statements on promising options, the following are the R&D activities that would support the development of fuel cycles that produce lower masses of SNF+HLW disposed per energy generated than the basis of comparison:

- 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.

D-2.2 Activity of SNF+HLW at 100 years per Energy Generated

Calculation of Metric Information

The SNF+HLW radioactivity (activity) value at 100 years after discharge is used as a metric for the Nuclear Waste Management criterion. The detailed nuclide information after discharge from a core is crucial in evaluating the activity of the SNF+HLW. The nuclide data at the charge and discharge states are obtained from the nuclide (isotope) data that were generated as part of the mass flow data tables presented in Appendix B-5 for the 40 Analysis Examples.

The assumptions for performing calculations on the Analysis Examples included that 0.2% of the charged fuel and 1.0% of discharged fuel was lost during fuel fabrication and reprocessing, respectively. For uniformity of the activity calculations, it was also assumed that the post-irradiation storage time was 5 years, any reprocessing was promptly completed, and the time required from fuel fabrication to fuel charging was 2 years. See more information on these items in Appendix B-5. The spent nuclear fuel (SNF) was defined as the direct disposal of discharged fuel (without reprocessing). SNF is generated by all once-through and limited recycle fuel cycles fuel cycle options, but not by the continuous recycle fuel cycle options where all irradiated (used) fuel is reprocessed and only HLW is disposed.

The collection of SNF and HLW nuclide information for activity calculations is explained using Figure D-2.1.1 and Table D-2.1.1 in Section D.2.1, which are the Material Flow Diagram and the Mass Flow Data, respectively, for the Analysis Example of Evaluation Group EG13. This Analysis Example is a two-stage limited recycle option. The first stage contained Pressurized Water Reactors (PWRs) based on the design and performance of typical commercial PWRs utilizing low-enriched uranium (LEU) nuclear fuel with average discharge burnup of 50 GWd/t. The second stage, also containing PWR technology, involved a single recycle of plutonium recovered from the used nuclear fuel of the first stage. The PWR in the second stage was similar to that in the first stage, and its fuel average discharge burnup was 50 GWd/t.

For the first stage, there are two HLW (as defined in this report) streams: the material losses from reprocessing/separations, and the fission products (FP) and minor actinides (MA) disposed in HLW from reprocessing. The total mass, 1.044 t/GWe-yr, is composed of 0.025 t/GWe-yr of minor actinides and 1.019 t/GWe-yr of fission products. There is no SNF from the first stage because all of the discharged fuel (DF) is recycled, while the DF mass in the second stage was not recycled and is denoted as SNF. Since a 5-year post-irradiation cooling time was assumed, the nuclide compositions were obtained by modeling the 5-year decay of nuclides following discharge from a reactor or EDS.

Since the SNF+HLW consists of two streams, the creation time of each SNF+HLW stream varies as depicted in Figure D-2.2.1. In this figure, the discharge state is considered as the reference point (i.e., t=0) and t_r indicates the fuel residence time in the core. Since the activity metric was defined at 100 years after discharge, the actual decay time is different based on the creation time of each SNF+HLW stream. For instance, the HLW recovered from used fuel reprocessing decays for 95 years, while the SNF recovered from the discharge decays for 100 years.

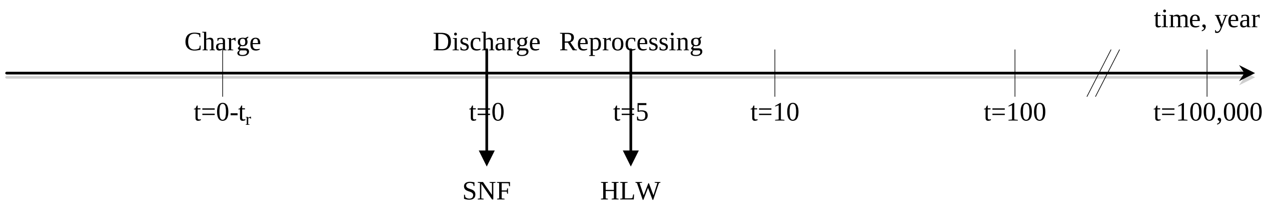


Figure D-2.2.1. Creation Time of SNF and HLW in a Typical Fuel Cycle Option.

The data for activity of SNF+HLW at 100 years after discharge have been appropriately renormalized to account for the fact that the mass flow data in Appendix B-5 have been put on an equal basis of 33% thermal efficiency for the irradiation system as described in Section D-1. The renormalization factors are contained in Table D-1.1 and for EG13, the factor is 1.01(actually 1.0091). The activities of SNF+HLW for the 40 Analysis Examples for the Evaluation Groups are provided in Figure D-2.2.2.

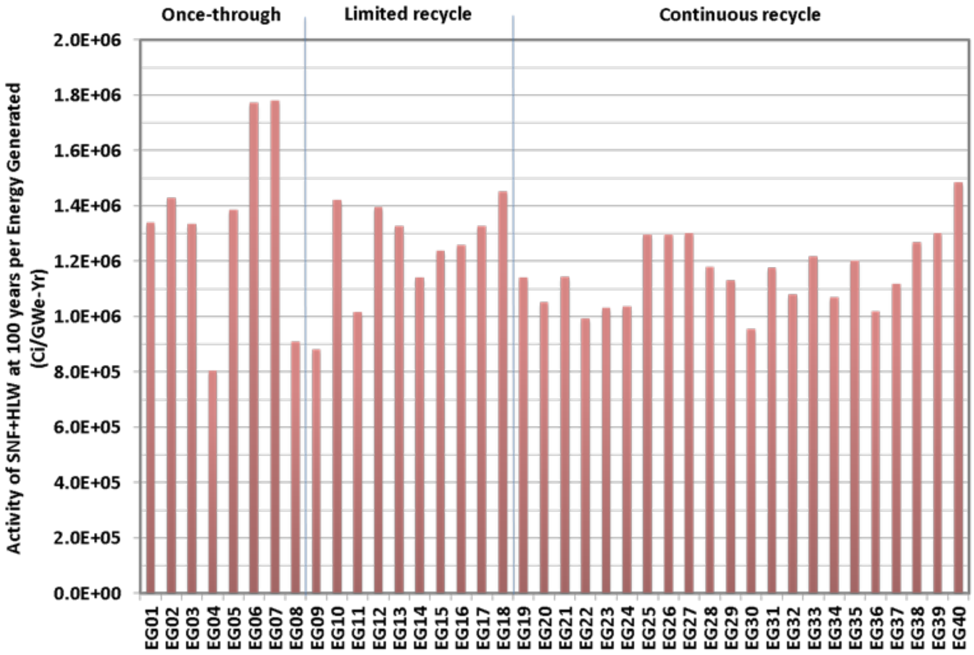
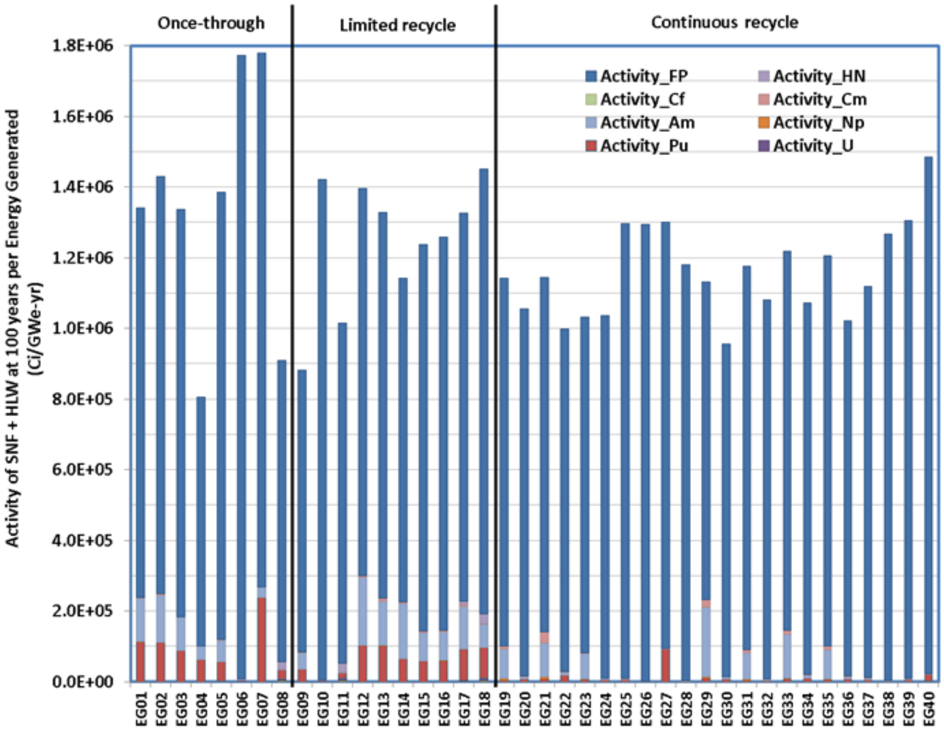


Figure D-2.2.2. Calculated Activity of SNF+HLW at 100 years per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

To further aid the understanding of trends in the results, the contributing elements to the activity of SNF+HLW at 100 years are provided in Figure D-2.2.3 for the Analysis Examples of the 40 Evaluation Groups. It is evident that the contributions from fission products (FP) dominate the activity of SNF+HLW at 100 years. At 100 years, there are contributions from other elements, but those are collectively at most less than 20% of the total activity. Another set of data pertinent to understanding the activity results is the mass of FP in the SNF+HLW, given the importance of fission products indicated by Figure D-2.2.3. The fission product mass as discharge is shown in Figure D-2.2.4 for the 40 Analysis Examples. This information shows that the fission products contributions are generally about 1.14 t/GWe-yr, which is consistent with basic physics considerations. The noticeable variations from this value are for Analysis Examples that include externally driven systems (e.g., EG06, EG07, EG08, EG33, EG34, and EG40, etc.) because extra fission energy is necessary to support auxiliary EDS components (such as accelerators in ADS). Of these Evaluation Groups, the difference for EG07 is the most pronounced and arises from the use of an ADS in a single-stage once-through fuel cycle and the fact that the accelerator needs energy input for driving the ADS. Effects are less pronounced for the FFH system, because in this case, it is assumed that the fusion power level has been set to offset the energy requirement of auxiliary systems. Because the current work is an Evaluation and Screening of fuel cycle options and not technologies, this large difference is accounted for in binning EG07 for the metrics for SNF+HLW activity at 100 years.



(Note that FP: Fission products; Cf: Californium; Cm: Curium; Am: Americium; Np: Neptunium; Pu: Plutonium; U: Uranium; Th: Thorium; HN: Other heavy metal elements)

Figure D-2.2.3. Contributors to Activity of SNF+HLW at 100 years per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

Across the 40 Analysis Examples, about 92% of the SNF+HLW activity at 100 years is due to the fission products (FP), about 3% due to plutonium (Pu), and 4% due to Americium (Am):

- Among the fission products, the leading nuclides are Cs-137 (and its beta-daughter Ba-137m) and Sr-90 (and its beta-daughter Y-90) with half-lives of 30 and 29 years, respectively.
- Among the Pu isotopes, the leading isotope is Pu-238 with a half-life of 88 years but others isotopes such as Pu-239, Pu-240 and Pu-241 can also be significant in the activity of plutonium.
- Among the Am isotopes, the leading isotope is Am-241 with a half-life of 432 years and which comes from the decay of Pu-241, which has a half-life of 14.4 years.

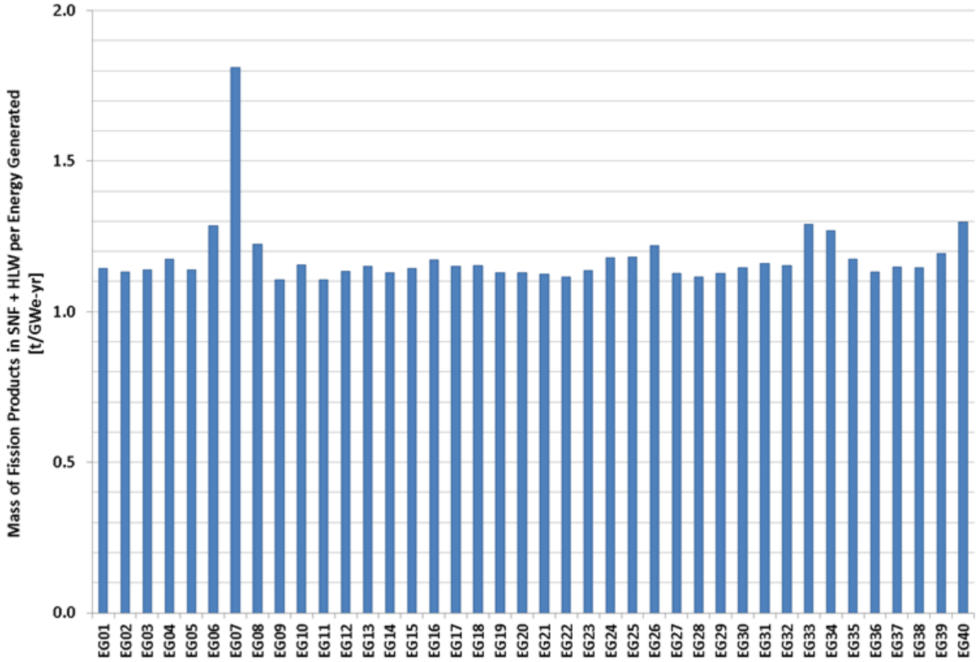


Figure D-2.2.4. Mass of Fission Products at 100 years in SNF+HLW Disposed per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

The variation by a factor of 2.2 in the activity at 100 years is primarily due to the variation in the quantity and specific activity of the fission products. The fission product mass varies with the effective thermal efficiency of the systems while the specific activity of the fission products varies with the origin of the fission and the residence time in the reactor. Secondly, the presence of Pu-241 and its decay daughter Am-241 also affects the 100-year activity.

Development of Metric Data

The calculated activity of SNF+HLW at 100 years disposed per energy generated is displayed in Figure D-2.2.5 along with the bin boundaries for this metric. On Figure D-2.2.5, the calculated information is ordered from the lowest performing (highest activity) Evaluation Group to the highest performing (lowest activity) and does not reflect the re-binning of a few Evaluation Groups as discussed below.

The metric bins were defined to recognize the variability in the activity of SNF+HLW at 100 years per energy generated across the different fuel cycle options included in an Evaluation Group, and in consideration of the following factors:

- Calculated activity of SNF+HLW at 100 years per energy generated varies by a factor of ~2.2 between the maximum and minimum values over the Analysis Examples for the 40 Evaluation Groups (all values are within 45% of the average value).
- Provide differentiation in performance by considering bin boundaries at +/- 20% and at +/-50% of the EG01 value (basis of comparison value).

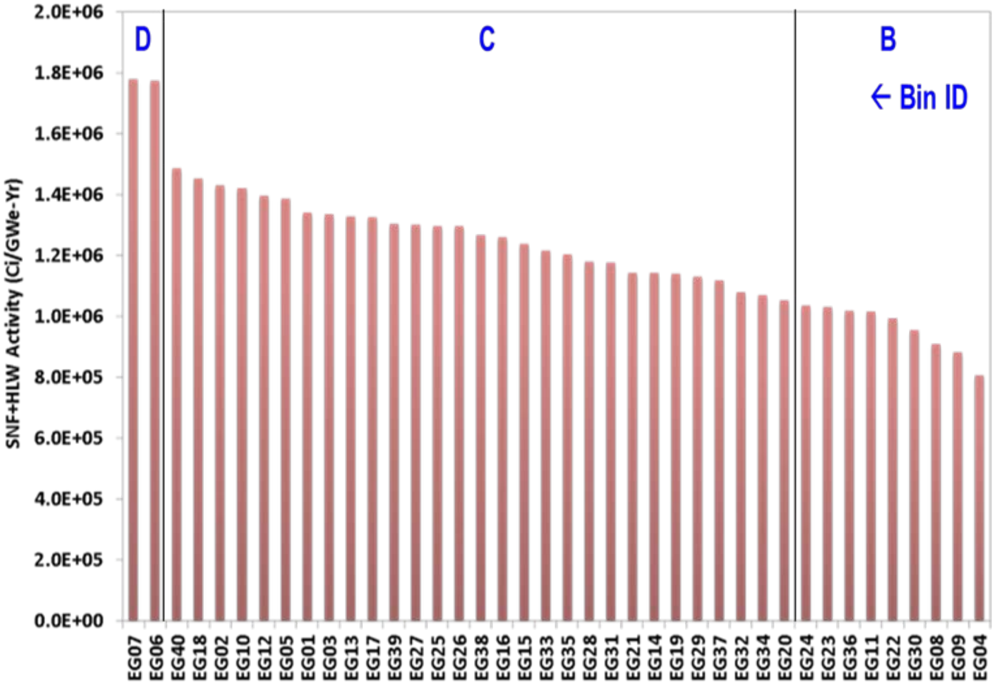


Figure D-2.2.5. Calculated Activity of SNF+HLW at 100 years per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Decreasing Activity.

With this information, the bins determined for the Metric of "activity of SNF+HLW at 100 years per energy generated", ranging from A (the highest performance bin) to E (the lowest performance bin), are presented in Table D-2.2.1.

Table D-2.2.1. Metric Bins for Activity of SNF+HLW at 100 years per Energy Generated.

Bin ID	Data Range (MCi/GWe-yr)	Bin Description
A	< 0.67	Activity of SNF+HLW at 100 years < 0.67 MCi/GWe-yr.
B	0.67 to < 1.05	Activity of SNF+HLW at 100 years ≥ 0.67 MCi/GWe-yr and < 1.05 MCi/GWe-yr; the lower bound for this bin is approximately 50% less than the activity for the Basis of Comparison.
C	1.05 to < 1.60	Activity of SNF+HLW at 100 years ≥ 1.05 MCi/GWe-yr and < 1.60 MCi/GWe-yr; Bin C contains the Basis of Comparison and the bin range is approximately ±20% of the Basis of Comparison.
D	1.60 to < 2.00	Activity of SNF+HLW at 100 years ≥ 1.60 MCi/GWe-yr and < 2.0 MCi/GWe-yr; the upper bound for this bin is approximately 50% greater than the activity of the Basis of Comparison.
E	≥ 2.00	Activity of SNF+HLW at 100 years ≥ 2.00 MCi/GWe-yr.

Note: 1 MCi = 10^6 Ci.

The bins that each Evaluation Group falls into are provided on Figure D-2.2.5 and Table D-2.2.2 (third column). For a few Evaluation Groups, the calculated Activity of SNF+HLW at 100 years per Energy Generated for the Analysis Example was not considered representative of the overall performance of that Evaluation Group, and a decision was made to reassign those Evaluation Groups to different bins. The fourth and fifth columns of Table D-2.2.2 are the final Metric Data and explanations for changes from the initial binning. The Evaluation Group EG07 was re-binned based on the realization that it would have given similar metric data result as EG08 if an FFH instead of ADS and similar modeling assumptions had been used in its Analysis Example and hence it is now in the same bin as EG08. Similarly, EG06 was re-binned in the same group as EG08, because even though it uses the same externally driven system, the assumptions for the burnup of EG06 was more conservative than that for EG08.

Table D-2.2.2. Metric Data for Activity of SNF+HLW at 100 Years per Energy Generated.

EG	**Calculated Mass (Ci/GWe-yr)**	**Analysis Example Bin Data**	**Metric Data**	**Reasons for Changing Analysis Example Bin Data**
EG01	1.34E+06	C	C	
EG02	1.43E+06	C	C	
EG03	1.34E+06	C	C	
EG04	8.05E+05	B	B	
EG05	1.39E+06	C	C	
EG06	1.77E+06	D	B	EG06 would have given similar metric data result as EG08 if similar modeling assumptions had been used in its Analysis Example.
EG07	1.78E+06	D	B	EG07 would have given similar metric data result as EG08 if an FFH instead of ADS and similar modeling assumptions had been used in its Analysis Example.
EG08	9.09E+05	B	B	
EG09	8.82E+05	B	B	
EG10	1.42E+06	C	C	
EG11	1.02E+06	B	B	
EG12	1.40E+06	C	C	
EG13	1.33E+06	C	C	
EG14	1.14E+06	C	C	
EG15	1.24E+06	C	C	
EG16	1.26E+06	C	C	
EG17	1.33E+06	C	C	
EG18	1.45E+06	C	C	
EG19	1.14E+06	C	C	
EG20	1.05E+06	C	C	
EG21	1.14E+06	C	C	
EG22	9.94E+05	B	B	
EG23	1.03E+06	B	B	
EG24	1.04E+06	B	B	
EG25	1.30E+06	C	C	
EG26	1.30E+06	C	C	
EG27	1.30E+06	C	C	
EG28	1.18E+06	C	C	
EG29	1.13E+06	C	C	
EG30	9.54E+05	B	B	

EG	Calculated Mass (Ci/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG31	1.18E+06	C	C	
EG32	1.08E+06	C	C	
EG33	1.22E+06	C	C	
EG34	1.07E+06	C	C	
EG35	1.20E+06	C	C	
EG36	1.02E+06	B	B	
EG37	1.12E+06	C	C	
EG38	1.27E+06	C	C	
EG39	1.30E+06	C	C	
EG40	1.49E+06	C	C	

*The light blue background is used to denote Evaluation Groups (EGs) with Analysis Examples using Th/U fuel; the light purple background denotes EGs with Th-only fuel, and the white background denotes Evaluation Groups with U-only fuel.

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.2.6 (note that the same data is provided in the fourth column of Table D-2.2.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

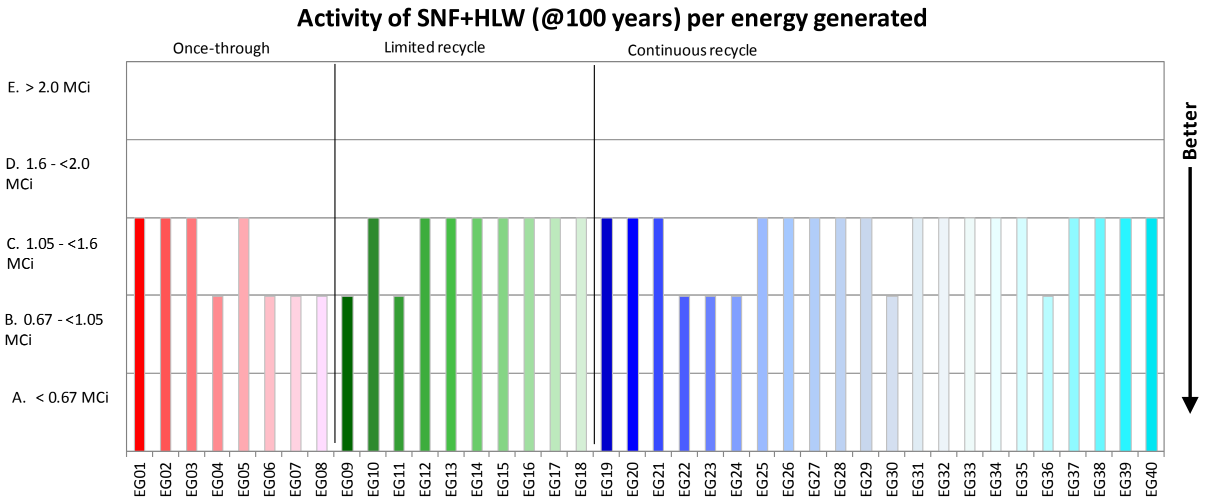


Figure D-2.2.6. Metric Data for Activity of SNF+HLW at 100 Years per Energy Generated for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups for Reducing Activity of SNF+HLW at 100 years

The Evaluation Group EG01, the Basis of Comparison, is in bin C because its Analysis Example has an activity of SNF+HLW per energy generated value of 1.34×10^6 Ci/GWe-yr (1.34 MCi/GWe-yr). No Analysis Example provides a 50% reduction in the activity of SNF+HLW relative to that of EG01 over all the 40 Evaluation Groups, hence there is no Evaluation Group in bin A. Additionally, no Evaluation Groups are in bins D and E. If the level of improvement represented by bin B was considered significant, then the corresponding set of Evaluation Groups meeting or exceeding that level of improvement is listed as promising. Those Evaluation Groups include:

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

The once-through options represented by EG04, EG06, EG07, and EG08, are in bin B, because the long residence time of fuel in the externally-driven system helps the reduction of the content of the high activity nuclides at time of fuel discharge. The other Evaluation Groups EG09 and EG11 are limited recycle cases, and EG22 to EG36 are continuous recycle cases. The limited recycle cases EG09 and EG11 also benefit from the long residence time of the fuel in the reactor. The common feature of the continuous recycle options (EG22, EG23, EG24, EG30, and EG36) is that they involve the recycle of all the transuranic elements, with the exception of EG23. In this regard, it is noted that not all of the continuous recycle options with recycle of the transuranic elements are in this list, e.g., the options EG20, EG32, and EG34 are not in the list. They are actually the better performing options in bin C (see the ordering of calculated data in Figure D-2.2.5).

Recall from Appendix C-1 that the activity at 100 years is being used as the measure of operational difficulty as well as the disposal loading issues. At 100 years and for hundreds of year thereafter, the decay heating is considered a relevant parameter for waste management. Since the metric provides the activity at 100 years, the data can be used to inform on the decay heat as well. Figure D-2.2.7 is provided in which values of activity and decay heat normalized to those of EG01 at 100 years are shown for each of the Analysis Examples of the 40 Evaluation Groups. The decay heat varies by a factor of 4.4 over the 40 Evaluation Groups (i.e., maximum to minimum values), while the activity only varied by a factor of 2.2 as noted above. It is evident from the figure that the generally better performance in decay heat of the continuous recycle options, i.e. EG19 to EG40, relative to EG01 tends to be suppressed by the use of activity as a measure (i.e. higher calculated activity data than decay heat data relative to EG01). Reduction in decay heat as high as a factor of more 3 is evident for some of these Evaluation Groups; it is 3.6 for EG30 relative to EG01 (activity difference is about 30%). There are also some once-through and limited recycle options for which large differences relative to EG01 are observed.

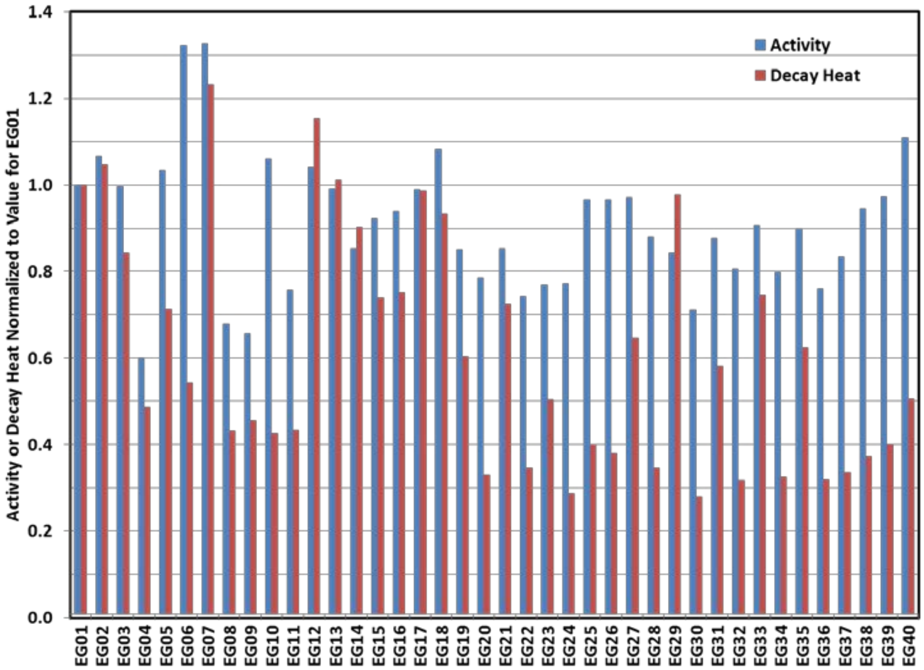


Figure D-2.2.7. Normalized Activity and Decay Heat of SNF+HLW at 100 Years per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

The reason for the large differences in the normalized data at 100 years is that different physics drive the behavior of activity and decay heat at that time point. The activity value is dictated predominantly by the content of the short-lived fission products which have half-life of about 30 years. On the other hand, the decay heat at 100 years after discharge is driven by the contents of both the actinides and the fission products. One consequence of using activity as a measure is that it does not well represent some of the effects of having a significant fraction of the actinides not sent into the high level waste stream but recycled instead, as in the continuous recycle options.

Based on decay heat at 100 years, the Evaluation Groups that would provide better performance than EG01 would mostly like include:

- EG20, EG22, EG24, EG28, EG30, EG32, EG34, EG36, and EG37 which all have a factor of about three or more reduction in the decay heat value for EG01, the basis of comparison. These are all continuous recycle cases.
- EG04, EG08 (and EG06 & EG07 based on previous arguments in Table D-2.2.1), EG09, EG10, EG11, EG13, EG23, EG25, EG26, EG38, and EG39 would be added if a factor of two lower decay heat value is considered important.

Note that using the decay heat at a single time is also not sufficient to characterize the impact of decay heat on disposal since repository loading is determined by the integrated decay heat from the time of placement (or closure of the repository) to the time of peak temperature, which could be 1000 years or more and is determined by the heat removal paths from the repository. The decay heat information is being provided here only as background, and was not used to influence the binning of the Evaluation Groups. However, the lower decay heat for some options provides initial insight into those options that may exhibit advantages for disposal (repository loading).

Supporting R&D and Insights

Based on the identified Evaluation Groups above, the following are the R&D activities that would support the development of fuel cycles that produce lower activity of SNF+HLW at 100 years per energy generated than the basis of comparison:

- 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 with all transuranic elements
- 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.

D-2.3 Activity of SNF+HLW at 100,000 years per Energy Generated

Calculation of Metric Information

The discussion of the approach for calculating the metric information for the activity of SNF+HLW at 100,000 years per energy generated for all the 40 Analysis Examples parallels the discussion provided in Appendix D-2.2 for the activity at 100 years. The same approach was used here.

The calculated values of activity of SNF+HLW at 100,000 years for the Analysis Examples for the 40 Evaluation Groups are provided in Figure D-2.3.1. It is noted that activity of SNF+HLW at 100,000 years after discharge is significantly lower than at 100 years (Figure D-2.2.2), and varies from 5.2 x 10^2 Ci/GWe-yr to 1.3 x 10^4 Ci/GWe-yr over the Analysis Examples for the 40 Evaluation Groups.

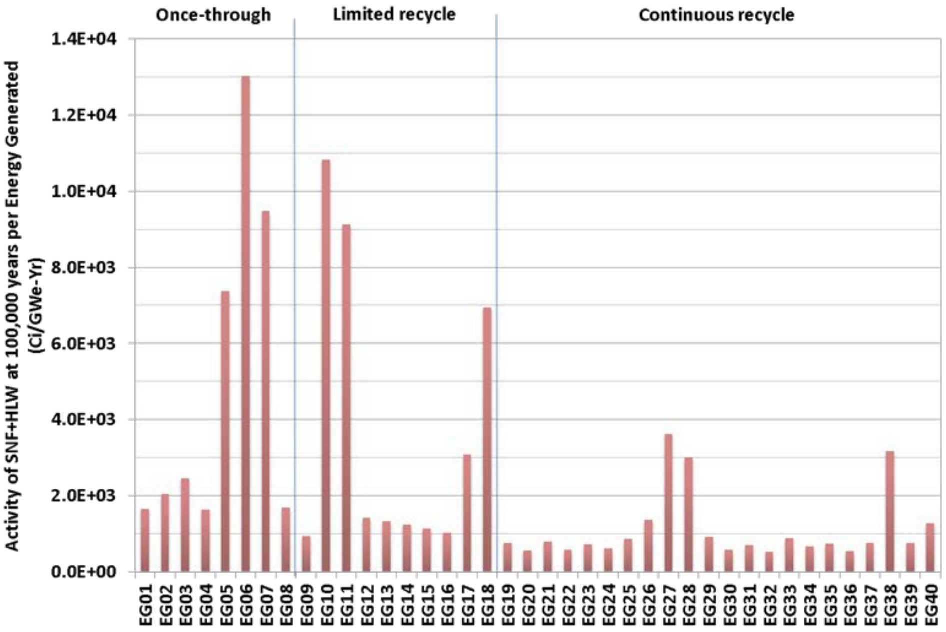
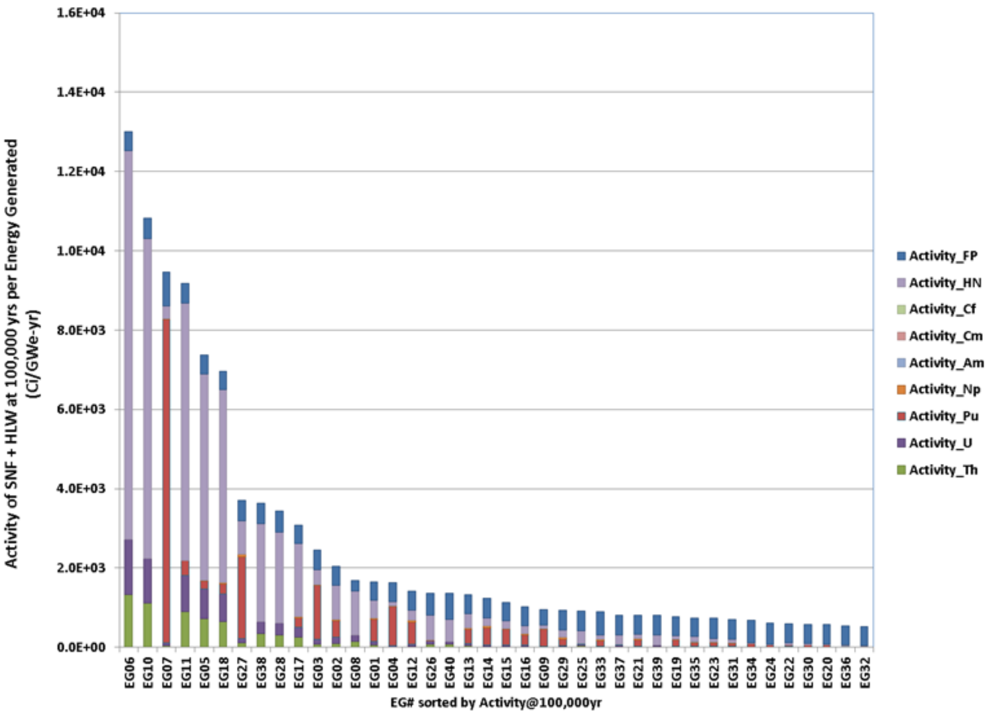


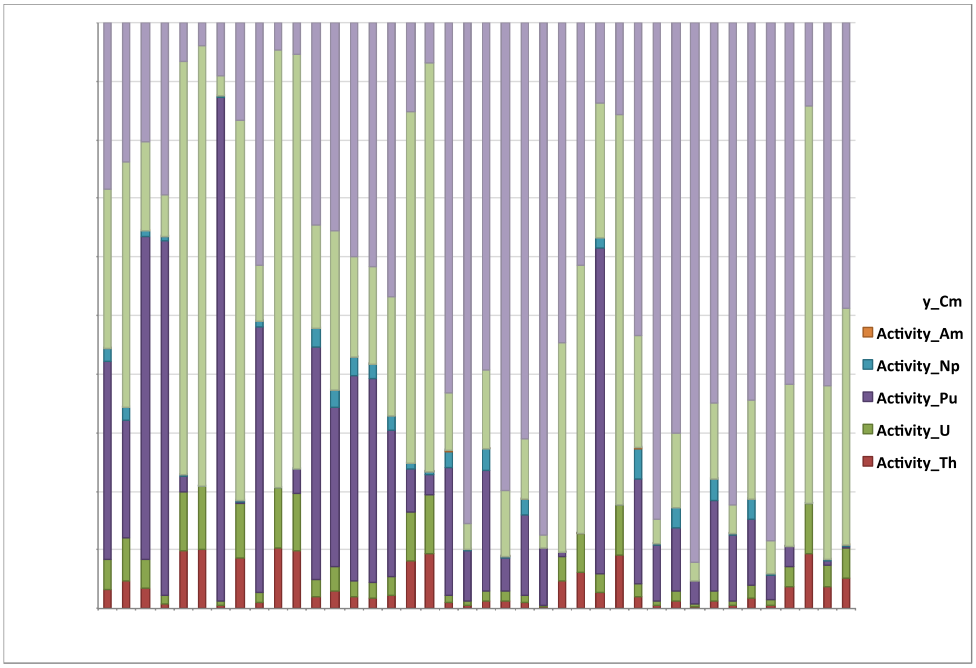
Figure D-2.3.1. Calculated Activity of SNF+HLW at 100,000 Years per Energy Generated for the Analysis Examples of the 40 Evaluation Groups.

The activity of SNF at 100,000 years is not well correlated with the activity at 100 years. There is a factor of 25 between the lowest and highest activity of SNF at 100,000 years values, compared to a factor of about 2.2 at 100 years. To further aid the understanding of trends in the results, the contributing elements to the activity of SNF+HLW at 100,000 years are provided in Figure D-2.3.2. The percent contributions from each element are provided in Figure D-2.3.3. At 100,000-years, the contribution from fission products is not as dominant as it was at 100 years. In some continuous recycling options such as EG32, the fission products are the main component of the long-term activity. In general, uranium, thorium, the other actinides, and other heavy elements (including those that arise mainly from the decay of other actinides) are responsible for a large fraction of the activity at 100,000 years. Plutonium is also a leading contributor in the U/Pu options.



(FP: Fission products; Cf: Californium; Cm: Curium; Am: Americium; Np: Neptunium; Pu: Plutonium; U: Uranium; Th: Thorium; HN: Other heavy metal elements)

Figure D-2.3.2. Activity of SNF+HLW at 100,000 Years Sorted in Descending Order for the Analysis Examples of the 40 Evaluation Groups.



(FP: Fission products; Cf: Californium; Cm: Curium; Am: Americium; Np: Neptunium; Pu: Plutonium; U: Uranium; Th: Thorium; HN: Other heavy metal elements)

Figure D-2.3.3. Contributors to Activity of SNF+HLW at 100,000 Years per Energy Generated for the Analysis Examples of the 40 Evaluation Groups.

- Among the fission products, the leading nuclides are Tc-99, Cs-135 and Zr-93. These would not be investigated further since all Analysis Examples have a relatively similar contribution attributable to the fission products.
- Among the Pu isotopes, the leading isotope is Pu-239 with a half-life of 24,100 years.
- Among the uranium isotopes, the leading isotope is U-233 with a half-life of 159,200 years. It decays into highly active heavy nuclei such as Th-229, Ac-225, Ra-225, Fr-221, At-217, Po-213, Bi-213 and Pb-209 that are responsible for higher SNF+HLW activity.

As a consequence, the variation by a factor of 25 in the activity at 100,000 years is primarily explained by the quantities of U-233 and Pu-239 disposed as waste. Accordingly, there are two factors of variations to take into account: (1) Th/U or U/Pu fuel cycles and (2) Reprocessing.

For the first point, as observed in Figure D-2.3.4, the decay of U-233 leads to a much larger activity at 100,000 years, by a factor ~15, when compared to the decay of Pu-239. This is because U-233 decay products are more radioactive than those from Pu-239. U-233 is mainly responsible for the long-term activity of Th/U fuel cycles while Pu-239 is mainly responsible for the long-term activity of U/Pu fuel cycles. Consequently, the thorium-fuel cycles have the highest activities at 100,000 years. This is the case for EG06 and EG10 that send 0.25 and 0.19 t (U-233/protactinium)/GWe-yr, respectively, into the SNF component, but also for EG11, EG05 and EG18. The only outlier is for EG07, which has the third highest 100,000-year activity while being a once-through U/Pu fuel-cycle. This is because 2.5 t/GWe-yr of plutonium is sent to SNF in EG07, which is ten times more than that for the Analysis Example EG01 (and in addition it has a higher isotopic content in Pu-239 because of the fast spectrum). The second point is that fuel cycles with continuous recycling usually achieve the lowest values of 100,000-year activity when U-233 and Pu are being recovered and recycled so that only FP and processing loss amounts of actinides are being sent to waste. This is the case for the continuous recycle evaluation groups (EG19 and above) except for EG27, EG28 and EG38, because of the relatively large quantity of Pu or U-233 being sent to the HLW through their reprocessing losses.

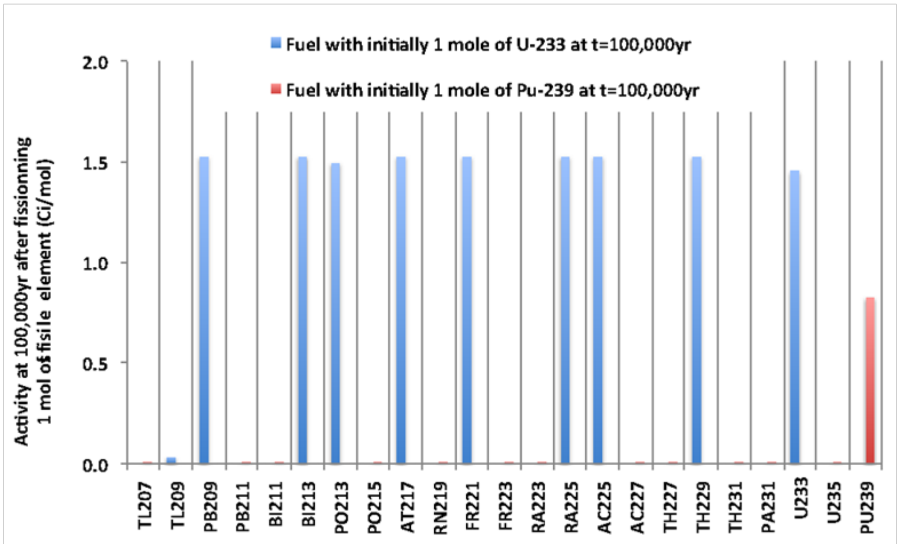
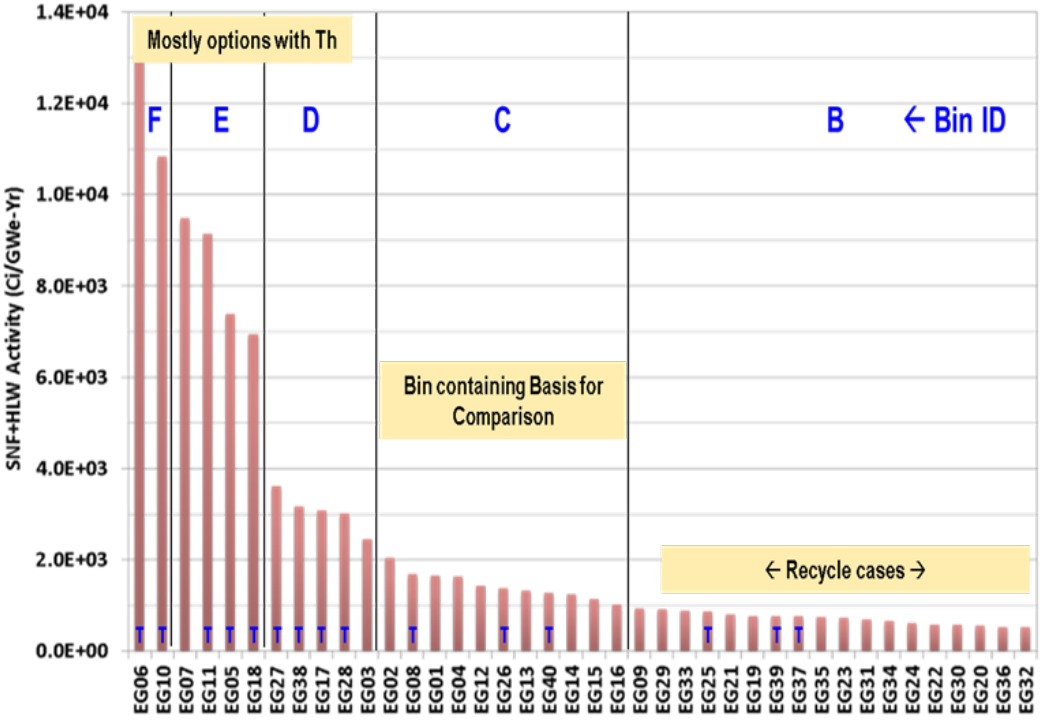


Figure D-2.3.4. Comparison of the Main Isotopic Components of the Activity at 100,000 Years from Decay Products of U-233 and Pu-239.

Development of Metric Data

The calculated activity of SNF+HLW at 100,000 years disposed per energy generated is displayed in Figure D-2.3.5 along with the bin boundaries. On Figure D-2.3.5, the calculated information has been ordered from the lowest performing (highest activity) Evaluation Group to the highest performing (lowest activity) and does not reflect the re-binning of a few evaluations groups as discussed below.



Note: The "T" at the bottom of a bar denotes Evaluation Groups with Analysis Examples using Th/U fuel or Th-only fuel.

Figure D-2.3.5. Calculated Activity of SNF+HLW at 100,000 Years per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Decreasing Activity.

The metric bins were defined to recognize the variability in the activity of SNF+HLW at 100,000 years per energy generated across the different fuel cycle options included in an evaluation group, and in consideration of the following factors:

- Calculated activity of SNF+HLW at 100,000 years per energy generated varies by a factor of ~25 between the maximum and minimum values over the 40 Analysis Examples for the Evaluation Groups.
- Provide differentiation in performance by considering the trends in the results.

With this information, the bins that were determined for the activity of SNF+HLW at 100,000 years per energy generated metric, ranging from A (the highest performance bin) to F (the lowest performance bin), are presented in Table D-2.3.1.

The bins for all of the Analysis Examples are provided in Figure D-2.3.5. For a few Evaluation Groups, the calculated Activity of SNF+HLW at 100,000 years per Energy Generated for the Analysis Example was not considered representative of the overall performance of that evaluation group, and a decision was made to reassign those Evaluation Groups to different bins. With the exception of EG06 and EG07, the re-binning for the other Evaluation Groups was informed by the inhalation and ingestion radiotoxicity for the 40 Evaluation Groups because the activity at 100,000 years is a surrogate for these parameters. The radiotoxicity of the emplaced wastes is the reason that isolation such as that provided by deep geologic disposal is required, and reflects the challenge that the repository system must overcome.

Table D-2.3.1. Metric Bins for Activity of SNF+HLW at 100,000 Years per Energy Generated.

Bin ID	Data Range (MCi/GWe-yr)	Bin Description
A	$< 5.0 \times 10^{-4}$	Activity of SNF+HLW at 100,000 years $< 5.0 \times 10^{-4}$ MCi/GWe-yr.
B	5.0×10^{-4} to $< 1.0 \times 10^{-3}$	Activity of SNF+HLW at 100,000 years $\geq 5.0 \times 10^{-4}$ MCi/GWe-yr and $< 1.0 \times 10^{-3}$ MCi/GWe-yr.
C	1.0×10^{-3} to $< 2.3 \times 10^{-3}$	Activity of SNF+HLW at 100,000 years $\geq 1.0 \times 10^{-3}$ MCi/GWe-yr and $< 2.3 \times 10^{-3}$ MCi/GWe-yr; Bin C contains the Basis of Comparison and the bin range is approximately ±40% of the Basis of Comparison.
D	2.3×10^{-3} to $< 5.0 \times 10^{-3}$	Activity of SNF+HLW at 100,000 years $\geq 2.3 \times 10^{-3}$ MCi/GWe-yr and $< 5.0 \times 10^{-3}$ MCi/GWe-yr.
E	5.0×10^{-3} to $< 1.0 \times 10^{-2}$	Activity of SNF+HLW at 100,000 years $\geq 5.0 \times 10^{-3}$ MCi/GWe-yr and $< 1.0 \times 10^{-2}$ MCi/GWe-yr.
F	$\geq 1.0 \times 10^{-2}$	Activity of SNF+HLW at 100,000 years $\geq 1.0 \times 10^{-2}$ MCi/GWe-yr.

Note: 1 MCi = 10^6 Ci.

The inhalation and ingestion radiotoxicity values for SNF+HLW at 100,000 years after discharge were calculated using the formulas (D-2.3.1) and (D-2.3.2), respectively.

$$T^{ingestion}(t) = \sum_{i=Isotopes} A_i(t) * e_i^{ingestion} \qquad \text{(D-2.3.1)}$$

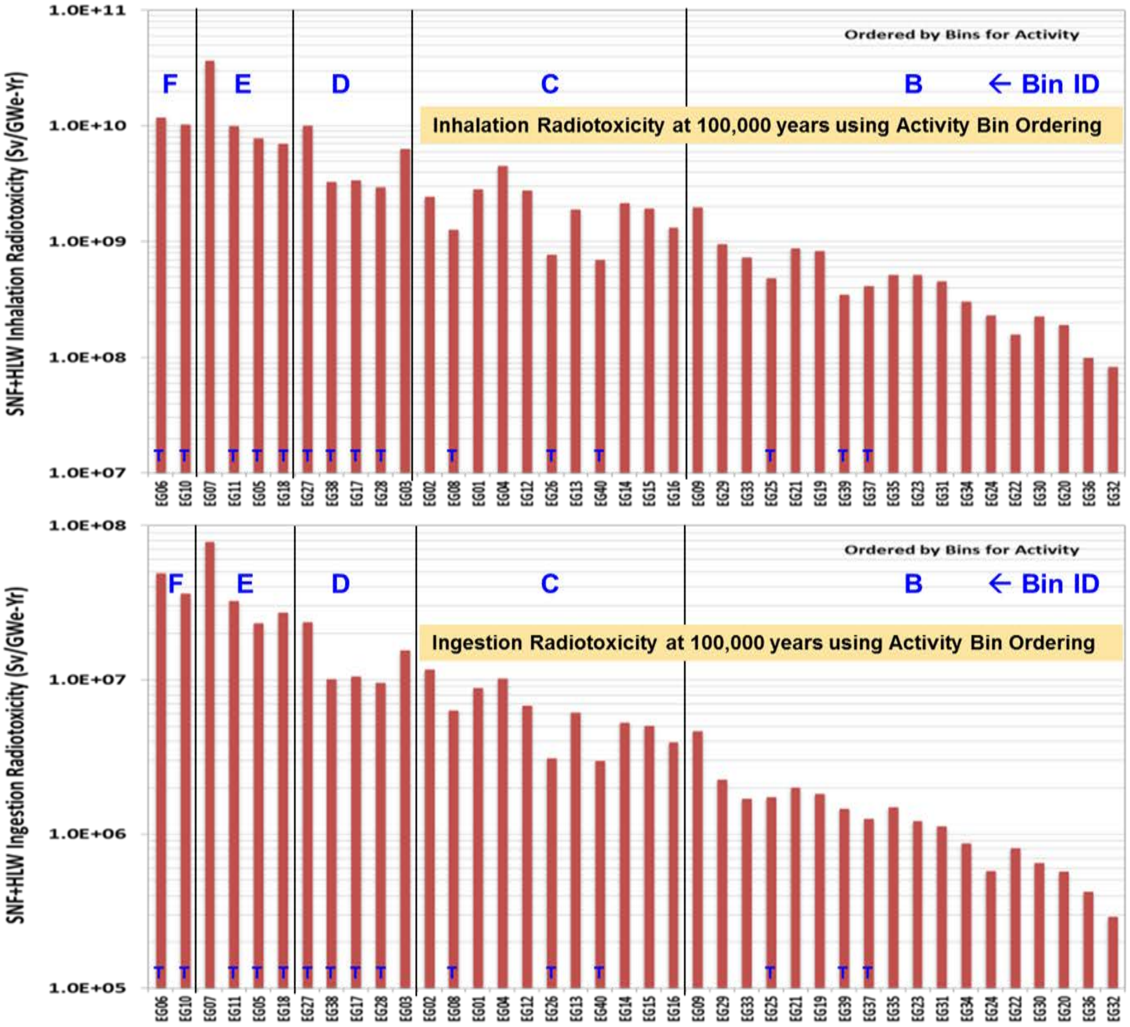
$$T^{inhalation}(t) = \sum_{i=Isotopes} A_i(t) * e_i^{inhalation} \qquad \text{(D-2.3.2)}$$

where

- T_i = ingestion/inhalation Toxicity for isotope *i*, [Sv],
- A_i = activity for isotope *i* [Bq],
- e_i = effective ingestion/inhalation dose conversion factor for isotope *i* [Sv/Bq].

The dose conversion factors are obtained from the ICRP for 737 isotopes. [D-2.3.1]

The process for using the radiotoxicities to correct the binning of Evaluation Groups involved plotting the radioactivity values in the same order as that used for Figure D-2.3.5. The resulting data is provided in Figure D-2.3.6. The figure was then used to determine which Evaluation Groups would need to be re-binned to obtain a decreasing ordering of the radiotoxicity values.



Note: The "T" at the bottom of a bar denotes Evaluation Groups with Analysis Examples using Th/U fuel or Th-only fuel.

Figure D-2.3.6. Radiotoxicity Data for Informing Binning of the Results for Activity of SNF+HLW at 100,000 Years per Energy Generated Ordered by Decreasing Activity.

The Metric Data results and the basis for any re-binning are provided in Table D-2.3.2.

Table D-2.3.2. Metric Data for Activity at 100,000 Years per Energy Generated.

EG	Calculated Mass (Ci/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG01	1.65E+03	C	C	EG01 could have been moved to D, but left unchanged since activity bin boundaries were determined based on this group, and it is considered as high value range for bin C (in radiotoxicity ordering).
EG02	2.05E+03	C	C	Could have been moved to D, but left unchanged accounting for the potential reduction of activity value by 50% by use of LWR system instead of

EG	Calculated Mass (Ci/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
				HTGR. Also based on ingestion radiotoxicity ordering, would be in group C.
EG03	2.46E+03	D	D	Could have been moved to E, but left unchanged as it is considered as the high value range for D.
EG04	1.64E+03	C	D	EG04 moved to bin D by consideration of its position in inhalation and ingestion radiotoxicity ordering.
EG05	7.38E+03	E	E	
EG06	1.30E+04	F	C	EG06 would have given similar metric data result as EG08 if similar modeling assumptions had been used in its Analysis Example.
EG07	9.48E+03	E	C	EG07 would have given similar metric data result as EG08 if an FFH instead of ADS and similar modeling assumptions have been used in its Analysis Example.
EG08	1.69E+03	C	C	
EG09	9.42E+02	B	C	EG09 moved to bin C by consideration of its position in inhalation and ingestion radiotoxicity ordering.
EG10	1.08E+04	F	E	EG10 moved to bin E by consideration of its position in inhalation and ingestion radiotoxicity ordering.
EG11	9.14E+03	E	E	
EG12	1.42E+03	C	C	
EG13	1.32E+03	C	C	
EG14	1.24E+03	C	C	
EG15	1.14E+03	C	C	
EG16	1.03E+03	C	C	
EG17	3.09E+03	D	D	
EG18	6.95E+03	E	E	
EG19	7.65E+02	B	B	
EG20	5.57E+02	B	B	
EG21	8.00E+02	B	B	
EG22	5.81E+02	B	B	
EG23	7.28E+02	B	B	
EG24	6.06E+02	B	B	
EG25	8.64E+02	B	B	
EG26	1.37E+03	C	B	EG26 moved to bin B by consideration of its position in inhalation and ingestion radiotoxicity ordering.
EG27	3.62E+03	D	E	EG27 moved to bin E by consideration of its position in inhalation and ingestion radiotoxicity ordering.
EG28	3.01E+03	D	D	
EG29	9.17E+02	B	B	
EG30	5.71E+02	B	B	
EG31	6.97E+02	B	B	
EG32	5.19E+02	B	B	

EG	Calculated Mass (Ci/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG33	8.79E+02	B	B	
EG34	6.69E+02	B	B	
EG35	7.41E+02	B	B	
EG36	5.35E+02	B	B	
EG37	7.62E+02	B	B	
EG38	3.17E+03	D	D	
EG39	7.63E+02	B	B	
EG40	1.28E+03	C	B	EG40 moved to bin B by consideration of its position in inhalation and ingestion radiotoxicity ordering.

*The light blue background is used to denote Evaluation Groups (EGs) with Analysis Examples using Th/U fuel; the light purple background denotes EGs with Th-only fuel, and the white background denotes EGs with U-only fuel.

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.3.7 (note that the same data is provided in the fourth column of Table D-2.3.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

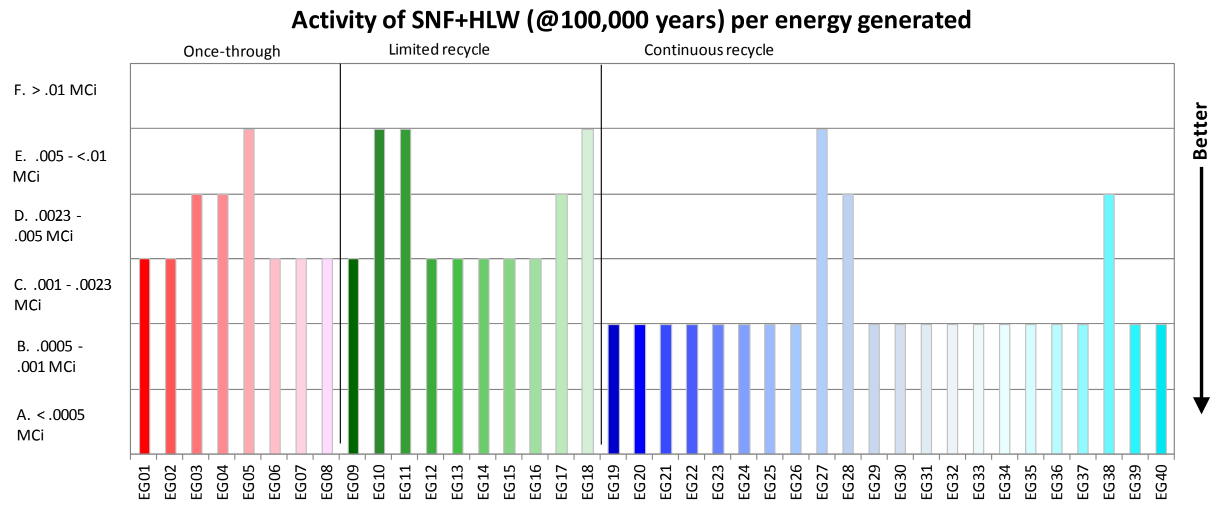


Figure D-2.3.7. Metric Data for Activity of SNF+HLW at 100,000 Years Disposed per Energy Generated for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups for Reducing Activity of SNF+HLW at 100,000 years

The Evaluation Group EG01, the basis of comparison, is in bin C because its Analysis Example has an activity of SNF+HLW at 100,000 years per energy generated value of 1.65 x10^3 Ci/GWe-yr. Note that no evaluation group is in bin A. Additionally, there are no Evaluation Groups in bin E.

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

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

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

As noted above, the radiotoxicity of SNF+HLW disposed has been derived from activity data at 100,000 years, representing the potential hazard if materials are released from a repository (see Figure D-2.3.6. The correlation coefficients of activity to the inhalation radiotoxicity and ingestion radiotoxicity data for 100,000 years are about 0.7 and 0.9, respectively. If reduction by a factor of about 10 or greater for both inhalation and ingestion radiotoxicity values is considered significant (best reduction for all EGs is a factor of about 30) then:

- EG20, EG22, EG24, EG30, EG32, EG34 and EG36 could be considered promising Evaluation Groups. They are all options involving continuous recycle of TRU. (Note that EG34 gives only a reduction by a factor of 9.3 for inhalation radiotoxicity and a factor of 10.2 for ingestion radiotoxicity).

Supporting R&D and Insights

Based on the identified Evaluation Groups above, the following are the R&D activities that would ensure the deployment and better performance of the Evaluation Groups

- Separation technologies for the limited and continuous recycle options
- Recycle fuels
- Advanced reactors
  - Fast-spectrum reactor and liquid fuel reactor (e.g., MSR) options
- Externally-driven systems utilizing extremely high burnup fuels (not needed for high performance however).

References for D-2.3

D-2.3.1. Annals of the ICRP, ICRP Publication 119, Compendium of Dose Coefficients based on ICRP Publication 60. Volume 41 Supplement 1 (2012)

D-2.4 Mass of DU+RU+RTh Disposed per Energy Generated

Calculation of Metric Information

The mass of DU+RU+RTh disposed per energy generated is defined as the sum of depleted uranium (DU), recovered uranium (RU), and recovered thorium (RTh) disposed from the fuel cycle option normalized to the energy generated by the option.

Similarly to the discussion of Appendix D-2.1 for the mass of SNF+HLW disposed per energy generated, the mass of DU+RU+RTh disposed per energy generated can be calculated from information contained in the Mass Flow Data for the 40 Analysis Examples (see Appendix B-5.1). The calculation approach is illustrated here again using Figure D-2.1.1 and Table D-2.1.1 of Section D-2.1, which show the “Material Flow Diagram” and “Mass Flow Data” for the Analysis Example for Evaluation Group EG13, which is a two-stage limited recycle case. Recall that the last column of Table D-2.1.1 indicates the net mass flow rate at the fuel cycle equilibrium state and the data in the table have a unit of metric ton per electricity generation of 100 GWe-yr. The signs (-) and (+) in Table D-2.1.1 indicate the feed and production to or from each technology category, respectively.

In order to generate the electricity of 100 GWe-yr, the Analysis Example for EG13 produces 14,983.3 tons of depleted uranium. Some of the recovered uranium is recycled in the Analysis Example, but a fraction, 1,634.9 tons, of the RU (extra) is directly disposed. Since the mass metric for the Evaluation and Screening needs to be normalized per unit energy generation, the DU+RU+RTh mass can be obtained by dividing the mass flow data values by 100 such as

- Mass of DU+RU+RTh per unit energy generation: (14,983.3 0 + 1,634.9)/100 = 166.18 t/GWe-yr

Using similar calculations, the mass of DU+RU+RTh disposed per energy generated by all the Analysis Examples for the 40 Evaluation Groups can be obtained from the "Mass Flow Data" and using the mass normalization factor from Table D-1.1. For example, the renormalization factor for EG13 is 1.0091, and therefore, the calculated normalized mass of DU+RU+RTh disposed is 167.69 t/GWe-yr.

The mass of DU+RU+RTh disposed per energy generated for all the 40 Analysis Examples for the Evaluation Groups are plotted in Figure D-2.4.1 for the 40 Evaluation Groups. Regardless of the fuel cycle, a sizeable amount of DU is produced for fuel cycles that need enriched uranium fuel. The once-through fuel cycle Analysis Example with PWRs that represents EG01 and which is the basis of comparison for the Evaluation and Screening produces 167 metric tons of DU in generating electricity of one GWe-yr. Another once-through fuel cycle Analysis Example using High Temperature Gas-cooled Reactors (HTGRs) that represents the Evaluation Group EG02 gives the highest DU mass of 296 t/GWe-yr because it requires a larger amount of uranium with higher enrichment on a per unit energy generation basis. The DU mass is zero for the fuel cycle options that do not need enriched uranium support, including the fuel cycle options that are fed thorium fuel only.

Figure D-2.4.1 shows that the Analysis Example for EG12 gives the highest RU mass. This is a two-stage limited recycle example in which the recovered Pu is recycled in a thermal spectrum system without enriched uranium support. The first stage uses HWRs, which breed Pu without enriched uranium support, and the recovered Pu from the stage is burnt once in the second stage utilizing PWR technology. As a result, EG12 does not produce DU, but it produces significant amount of RU from the initial NU fuel. The RU mass is zero for all once-through fuel cycle options. In addition, the RU mass is zero for the fuel cycle options that recycle the RU entirely or the fuel cycle options that are fed thorium fuel only.

Some fuel cycle options produce both DU and RU. For instance, the Analysis Example for EG13 is a two stage-limited recycle example in which the recovered Pu from the first stage that uses enriched uranium fuel is recycled in the thermal reactors of the second stage. Consequently, the option produces both DU and RU.

Among the 40 Analysis Examples, fifteen examples require thorium feed along with or without uranium feed. There is no RTh mass in all the Analysis Examples because the recovered thorium is entirely recycled in all of them.

In summary, the mass of DU+RU+RTh varies from 0 to 296 t/GWe-yr. Generally, DU is the dominant contributor to the mass of DU+RU+RTh and RU is the second leading contributor. There is no RTh for any of the 40 Evaluation Groups because of either no Th feed or complete recycle of the recovered Th. The Analysis Example for EG02 has the highest mass of DU+RU+RTh amongst the 40 Analysis Examples and those for several Evaluation Groups (EG03, EG04, EG06, EG07, EG08, EG09, EG10, EG14, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG38, and EG40) have zero DU+RU+RTh mass.

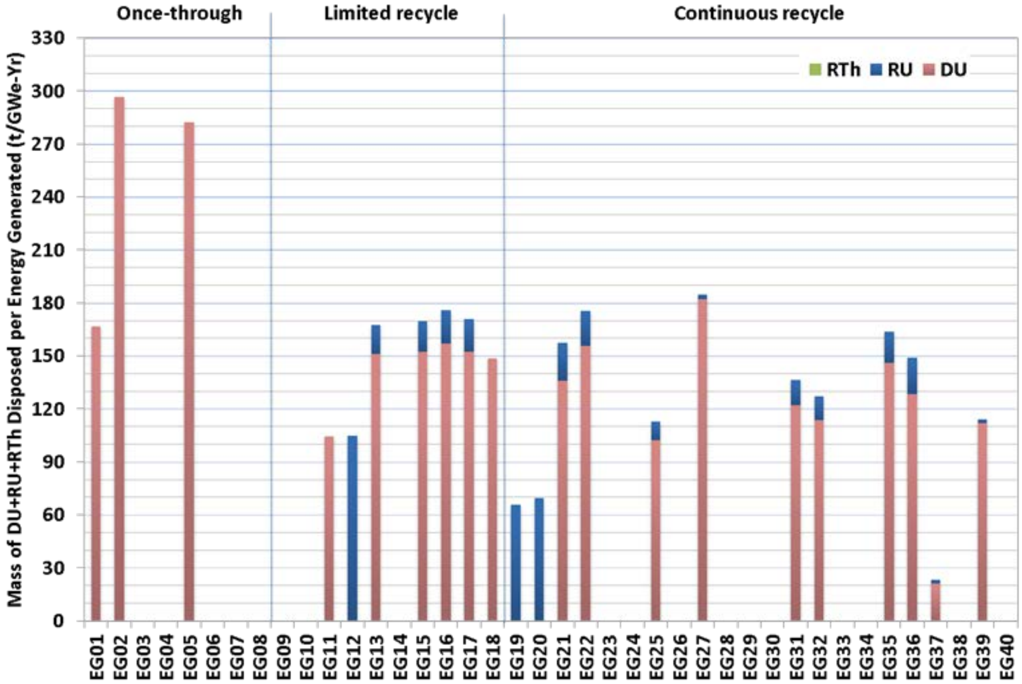


Figure D-2.4.1. Calculated Mass of DU+RU+RTh Disposed per Energy Generated for the Analysis Examples of the 40 Evaluation Groups.

Development of Metric Data

The 40 Analysis Examples provide an initial indication of the performance of the Evaluation Groups. Since there are many possible fuel cycle options in an Evaluation Group, it is realized that the metric information calculated for the Evaluation Group would show some variability. Consequently, it was determined that binning the metric information derived from the 40 Analysis Examples would better inform on the potential of the Evaluation Groups. In the following, the DU+RU+RTh mass calculated for the Analysis Example, the approach to binning, and for re-binning some evaluations groups are discussed.

The calculated mass of DU+RU+RTh disposed per energy generated is displayed in Figure D-2.4.2 along with the bin boundaries for the metric. On Figure D-2.4.2, the calculated information has been ordered from the lowest performing (highest mass) to the highest performing (lowest mass) and does not reflect the re-binning of a few evaluations groups as discussed below.

The metric bins were defined to recognize the variability in the mass of DU+RU+RTh disposed per energy generated across the different fuel cycle options included in an Evaluation Group, and in consideration of the following factors:

- Calculated mass of DU+RU+RTh disposed per energy generated varies by two orders of magnitude over the 40 Analysis Examples for the Evaluation Groups.
- Bins should recognize fuel cycles (once-through, limited and continuous recycle) and the magnitude of change of the metric over the 40 Evaluation Groups.
- The highest performing bin was defined by an upper boundary at ~1.0 t/GWe-yr, to separate no enrichment or significantly performing options.

With this information, the bins that were determined for the mass of DU+RU+RTh metric, ranging from A (the highest performance bin) to F (the lowest performance bin), are presented in Table D-2.4.1.

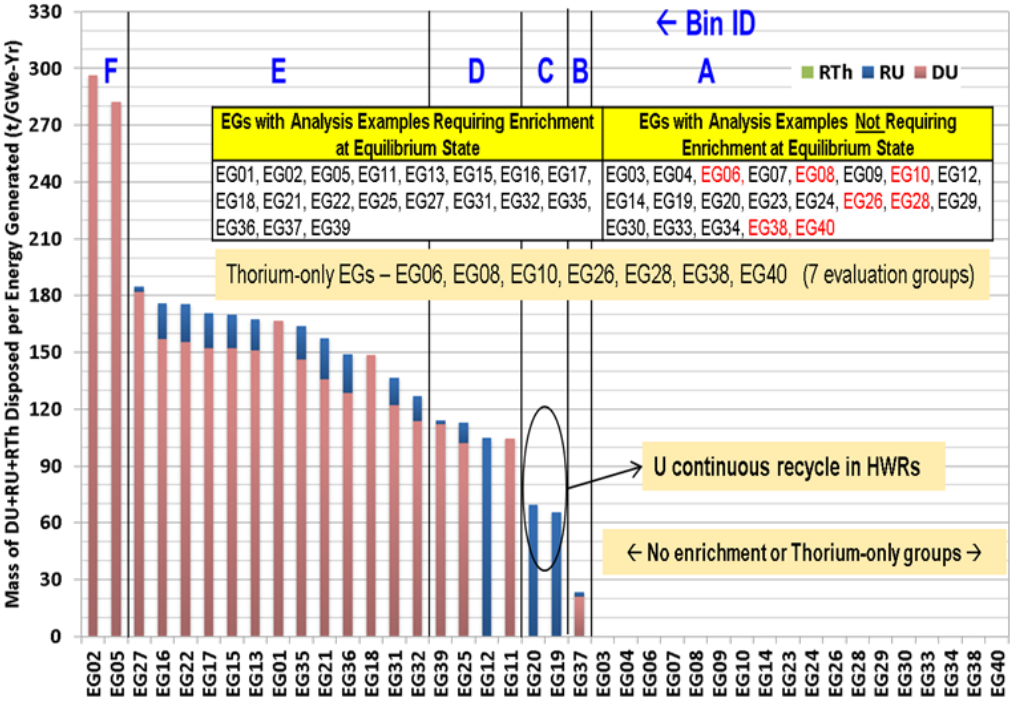


Figure D-2.4.2. Calculated Mass of DU+RU+RTh Disposed per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Decreasing Mass.

The bins obtained for the Evaluation Groups based on this approach are provided in Figure D-2.4.2 and Table D-2.4.2 (third column). For a few Evaluation Groups, the calculated Mass DU+RU+RTh disposed per Energy Generated for the Analysis Example was not considered representative of the overall performance of that Evaluation Group, and a decision was made to reassign those Evaluation Groups to different bins. In the fourth and fifth columns of Table D-2.4.2 are the final Metric Data and explanations for changes from the initial binning (reflecting the re-binning of data for EG02 and EG05). These two Evaluation Groups were re-binned from “F” to “E” based on the realization that they could have used an LWR instead of an HTGR which would have resulted in a similar metric data as the group with the basis of comparison (EG01).

Table D-2.4.1. Metric Bins for Mass DU+RU+RTh Disposed per Energy Generated.

Bin ID	Data Range (t/GWe-yr)	Bin Description
A	< 1	Mass DU+RU+RTh disposed < 1.0 t/GWe-yr
B	1 to < 40	Mass DU+RU+RTh disposed from 1.0 t/GWe-yr to < 40.0 t/GWe-yr
C	40 to < 80	Mass DU+RU+RTh disposed from 40.0 t/GWe-yr to < 80.0 t/GWe-yr
D	80 to < 120	Mass DU+RU+RTh disposed from 80.0 t/GWe-yr to < 120.0 t/GWe-yr
E	120 to < 200	Mass DU+RU+RTh disposed from 120.0 t/GWe-yr to < 200.0 t/GWe-yr; contains the basis of comparison (EG01)
F	≥ 200	Mass DU+RU+RTh disposed equals or greater than 200.0 t/GWe-yr

Table D-2.4.2. Metric Data for Mass of DU+RU+RTh Disposed per Energy Generated.

EG	Calculated Mass (t/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG01	166.67	E	E	
EG02	296.48	F	E	The Evaluation Group (EG02) could have used an LWR instead of an HTGR which would have resulted in a similar metric data as the group with the basis of comparison (EG01).
EG03	0.00	A	A	
EG04	0.00	A	A	
EG05	282.41	F	E	The Evaluation Group (EG05) could have used an LWR instead of an HTGR which would have resulted in a similar metric data as the group with the basis of comparison (EG01).
EG06	0.00	A	A	
EG07	0.00	A	A	
EG08	0.00	A	A	
EG09	0.00	A	A	
EG10	0.00	A	A	
EG11	104.29	D	D	
EG12	104.96	D	D	
EG13	167.69	E	E	
EG14	0.00	A	A	
EG15	169.81	E	E	
EG16	175.99	E	E	
EG17	170.88	E	E	
EG18	148.60	E	E	
EG19	65.54	C	C	
EG20	69.36	C	C	
EG21	157.51	E	E	
EG22	175.42	E	E	
EG23	0.00	A	A	
EG24	0.00	A	A	
EG25	112.81	D	D	
EG26	0.00	A	A	
EG27	184.74	E	E	
EG28	0.00	A	A	
EG29	0.00	A	A	
EG30	0.00	A	A	
EG31	136.55	E	E	
EG32	127.15	E	E	
EG33	0.00	A	A	
EG34	0.00	A	A	
EG35	163.92	E	E	
EG36	149.10	E	E	
EG37	23.42	B	B	
EG38	0.00	A	A	

EG	Calculated Mass (t/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG39	114.17	D	D	
EG40	0.00	A	A	

*The light blue background is used to denote Evaluation Groups with Analysis Examples using Th/U fuel; the light purple background denotes Evaluation Groups with Th-only fuel, and the white background denotes Evaluation Groups with U-only fuel.

The final metric bin data for the 40 Evaluation Groups are provided in Figure D-2.4.3 (note that the same data is provided in the fourth column of Table D-2.4.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

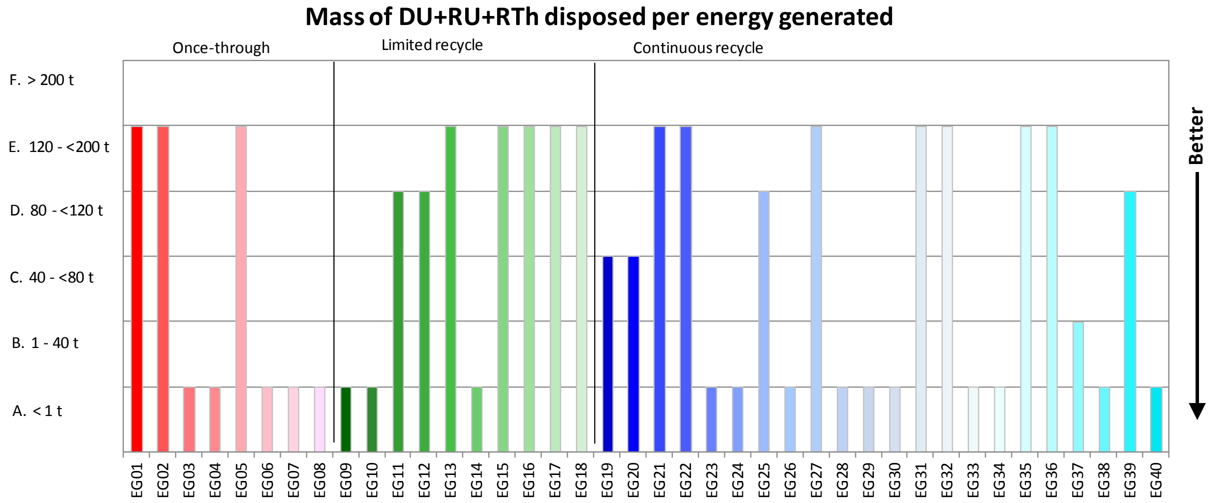


Figure D-2.4.3. Metric Data for the Mass of DU+RU+RTh Disposed per Energy Generated for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups for Reducing the Mass of DU+RU+RTh

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

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

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

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

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

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

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

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

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

Comparing bin mid-points, bin C provides more than a factor of 2 reduction in mass of DU+RU+RTh relative to bin E. As aforementioned, EG19 and EG20 do not require enrichment and have as Analysis Examples fuel cycle with uranium continuous recycle in HWRs. They fall in this group because natural uranium is used to replenish the fissile stock and ultimately recycled after use.

Bin D offers ~1.5 to 2 fold reduction in the mass of DU+RU+RTH (comparing bin mid-points), but this is not typically considered transformational in the mass of material to be disposed.

Supporting R&D and Insights

Based on the identified Evaluation Groups above, arising from the conditional statements on promising options, following are the R&D activities that would support the development of fuel cycles that produce lower masses of DU+RU+RTh disposed per energy generated than the basis of comparison:

- 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.

D-2.5 Volume of LLW per Energy Generated

As described in Appendix C-1.7, the volume of low-level waste for each of the 40 Evaluation Groups was calculated using the information that was developed for each of the Analysis Examples and the multipliers for each of the appropriate fuel cycle operations. The LLW volume data for the Analysis Examples are shown in Figure D-2.5.1.

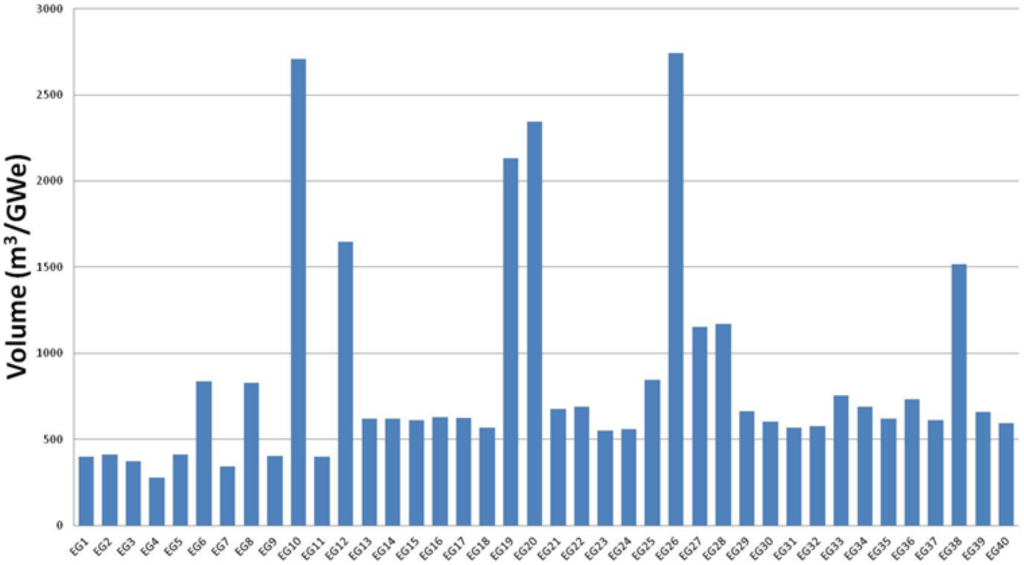


Figure D-2.5.1. Volume of LLW for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

The Analysis Examples were then placed into the bin structure that was developed in such a way as to identify fuel cycles that could achieve a significant degree of change from the Basis of Comparison. The center of this bin structure was set at 400 m³ per GWe-y. This midpoint value is based on the Basis of Comparison (EG01) low-level waste calculation shown in Appendix C-1.7 of 398.8 m³ / GWe-y.

The binning structure boundaries were established such that they divided the data range into five bins using an exponential curve as shown in Figure D-2.5.2. Bin "A" contains the smallest amount of low-level waste and Bin "E" represents the largest amount of low-level waste. Figure D-2.5.2 also shows the overlay of the exponential bin boundaries on the calculated low-level waste for the Analysis Examples that are ordered by increasing low-level waste volume.

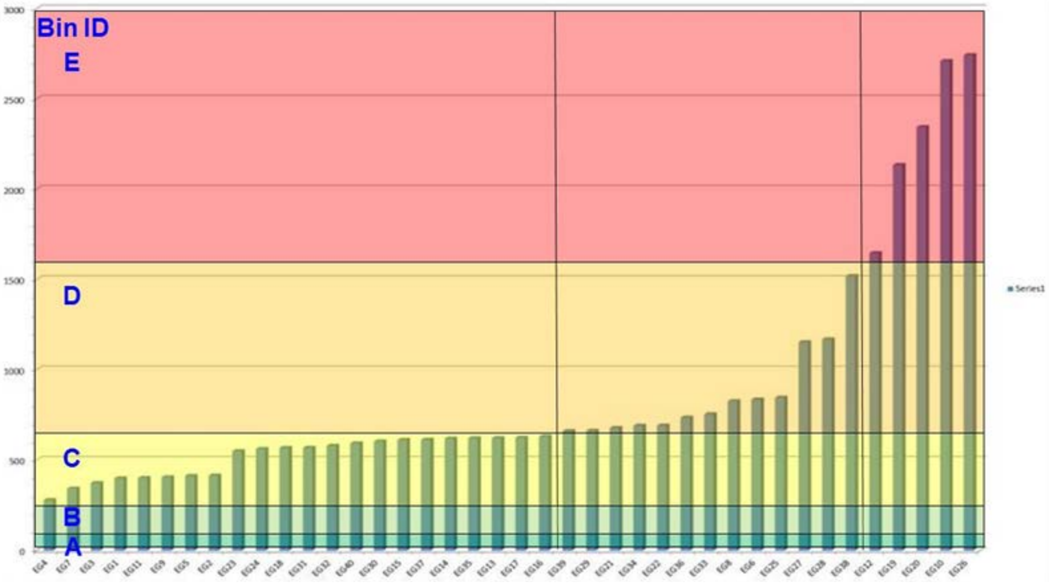


Figure D-2.5.2. Overlay of the Bins for LLW Waste Volume on the Analysis Example Results.

It is observed from this figure is that bins A and B are unpopulated but that several EGs (EG04, EG03, EG07) are relatively close to the bin boundary between C and B. The same three Evaluation Groups are slightly lower than the Basis of Comparison (EG01). They are also all once through options.

The bins that were determined for the volume of low level waste metric, ranging from A (the highest performance bin) to E (the lowest performance bin), are presented in Table D-2.5.1. The bins or metric data obtained for the Evaluation Groups based on this approach are provided in Table D-2.5.2 (third column).

Table D-2.5.1. Metric Bin for Volume of Low Level Waste Disposed per Energy Generated.

Bin ID	**Data Range (m^3/GWe-yr)**	**Bin Description**
A	< 100	Volume of LLW disposed < 100 m^3/GWe-yr
B	100 to < 252	Volume of LLW disposed 100 to < 252 m^3/GWe-yr
C	252 to < 634	Volume of LLW disposed 252 to < 634 m^3/GWe-yr; Contains Basis of Comparison
D	634 to < 1592	Volume of LLW disposed 634 to < 1592 m^3/GWe-yr
E	≥ 1592	Volume of LLW disposed ≥ 1592 m^3/GWe-yr

Table D-2.5.2. Results from the Analysis Examples and the Corresponding Metric Data for the 40 Evaluation Groups.

Evaluation Group	Volume LLW (m^3)	Metric Data	Range of the Bin
EG01	398.84	C	252 to < 634 m^3/GWe-yr
EG02	414.23	C	252 to < 634 m^3/GWe-yr
EG03	373.00	C	252 to < 634 m^3/GWe-yr
EG04	278.60	C	252 to < 634 m^3/GWe-yr
EG05	412.58	C	252 to < 634 m^3/GWe-yr
EG06	835.32	D	634 to < 1592 m^3/GWe-yr
EG07	342.20	C	252 to < 634 m^3/GWe-yr
EG08	826.47	D	634 to < 1592 m^3/GWe-yr
EG09	359.00	C	252 to < 634 m^3/GWe-yr
EG10	2796.69	E	≥ 1592 m^3/GWe-yr
EG11	401.01	C	252 to < 634 m^3/GWe-yr
EG12	1646.12	E	≥ 1592 m^3/GWe-yr
EG13	621.88	C	252 to < 634 m^3/GWe-yr
EG14	618.99	C	252 to < 634 m^3/GWe-yr
EG15	611.53	C	252 to < 634 m^3/GWe-yr
EG16	630.76	C	252 to < 634 m^3/GWe-yr
EG17	624.09	C	252 to < 634 m^3/GWe-yr
EG18	567.72	C	252 to < 634 m^3/GWe-yr
EG19	2134.12	E	≥ 1592 m^3/GWe-yr
EG20	2343.80	E	≥ 1592 m^3/GWe-yr
EG21	678.04	D	634 to < 1592 m^3/GWe-yr
EG22	691.19	D	634 to < 1592 m^3/GWe-yr
EG23	549.49	C	252 to < 634 m^3/GWe-yr
EG24	561.42	C	252 to < 634 m^3/GWe-yr
EG25	853.46	D	634 to < 1592 m^3/GWe-yr
EG26	2830.60	E	≥ 1592 m^3/GWe-yr
EG27	1160.73	D	634 to < 1592 m^3/GWe-yr
EG28	1168.72	D	634 to < 1592 m^3/GWe-yr

EG29	662.22	D	634 to < 1592 m^3/GWe-yr
EG30	602.99	C	252 to < 634 m^3/GWe-yr
EG31	567.85	C	252 to < 634 m^3/GWe-yr
EG32	579.27	C	252 to < 634 m^3/GWe-yr
EG33	753.51	D	634 to < 1592 m^3/GWe-yr
EG34	696.42	D	634 to < 1592 m^3/GWe-yr
EG35	621.45	C	252 to < 634 m^3/GWe-yr
EG36	735.16	D	634 to < 1592 m^3/GWe-yr
EG37	624.52	C	252 to < 634 m^3/GWe-yr
EG38	1518.73	D	634 to < 1592 m^3/GWe-yr
EG39	677.49	D	634 to < 1592 m^3/GWe-yr
EG40	592.98	C	252 to < 634 m^3/GWe-yr

The final metric bin data for the 40 Evaluation Groups are provided in Figure D-2.5.3 with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

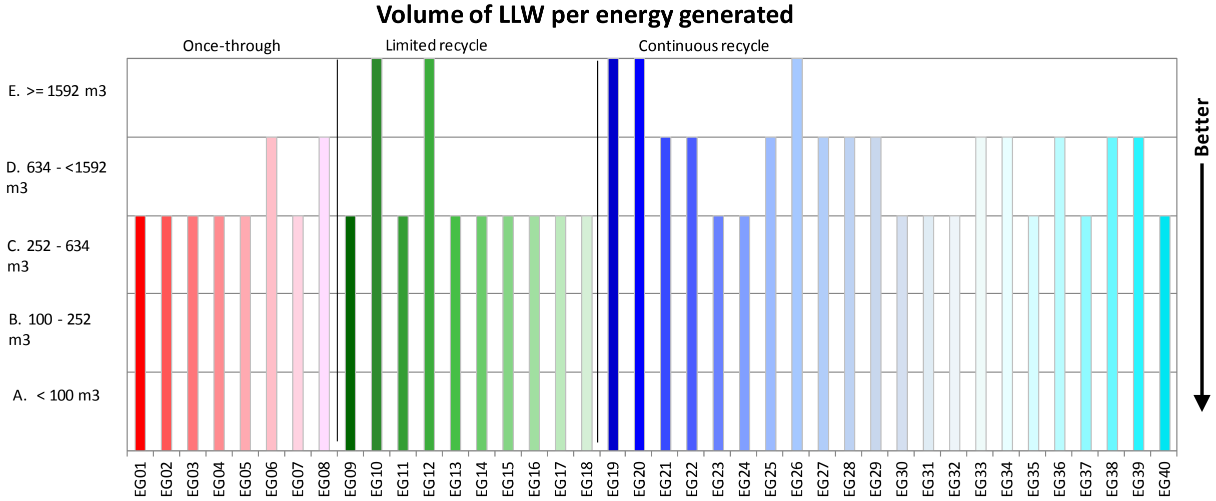


Figure D-2.5.3. Metric Data for the Volume of Low Level Waste per Energy Generated for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Description of the Metric Data

As previously noted, the LLW volume (metric data) was developed for each Evaluation Group using the methodology described in Appendix C-1.7. However, simply looking at the values of low-level waste generated does not provide a full understanding of its origin within the fuel cycle. Since the estimate was developed from the ground up we were able to examine the generation terms in several ways. The first was to look at the primary functions within the fuel cycle. The same data shown in Figure D-2.5.1 is divided into these functional elements and shown in Figure D-2.5.4. There are several aspects to become apparent from this figure. The first is that the reactor component is relatively uniform across all of the Evaluation Groups. The second is that the enrichment component is relatively small. The third aspect is that reprocessing component is not a dominant term in many of the full recycle cases.

There are six Evaluation Groups that show the greatest low-level waste generation terms (EG10, EG12, EG19, EG20, EG26, and EG38). Three of these are heavy water reactor cases with recycle (EG12, EG19, EG20). The low-level waste generation associated with recycle for the heavy water reactor cases is driven by the large mass of fuel that must be processed. Two of the three remaining cases (EG10, EG26) are molten salt reactor systems here again the waste associated with the continuous online processing of a large quantity of fuel is the driver. The last case (EG38) is dominated by extensive processing requirements which in turn result in large quantities of low-level waste production. If these six cases are excluded then the range of low-level waste generated is ~280 to 1170 m³ per GWe-y.

Two other points need to be made from the data shown in this figure. The first is that once through systems do not always result in the lowest volume of low-level waste. The second is that, in general, limited recycle and continuous recycle scenarios resulted in more low-level waste produced than once through fuel cycles.

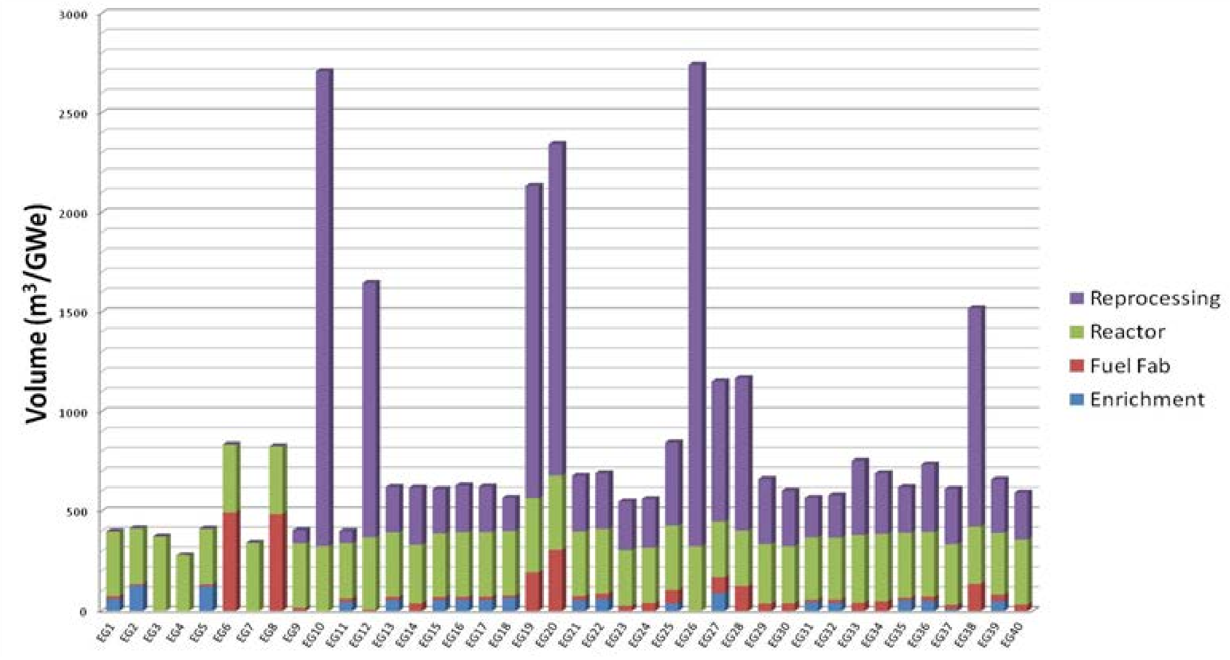


Figure D-2.5.4. LLW Production by Fuel Cycle Function for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

Discussion of the Composition of the Analysis Example Results

Additional insight can be gained by examining the makeup of the types of waste. Figure D-2.5.5 shows the origin of the waste in terms of process low-level waste, process greater than class C (GTCC) waste, D&D low-level waste and D&D GTCC waste. Examination of this figure shows that the GTCC component is on the order of <10% of the total low-level waste generated. The second aspect that is apparent is that the processing waste in nearly every case is equal to or greater than the D&D waste. The D&D waste is impacted significantly by the anticipated life of the facility and by the facility design. By careful design of the facility it may be possible to significantly reduce the volume of waste that must be handled as low-level waste during the D&D operations. This however requires significant upfront planning in the facility design. It should also be noted that the data used to generate these estimates would have been based on first and second generation facility designs that may not have included these newer types of features. The operational low-level waste associated with EG 10 and EG 26 are again tied to the large mass of material handled in the MSR processing and very limited experience was available upon which to base these estimates.

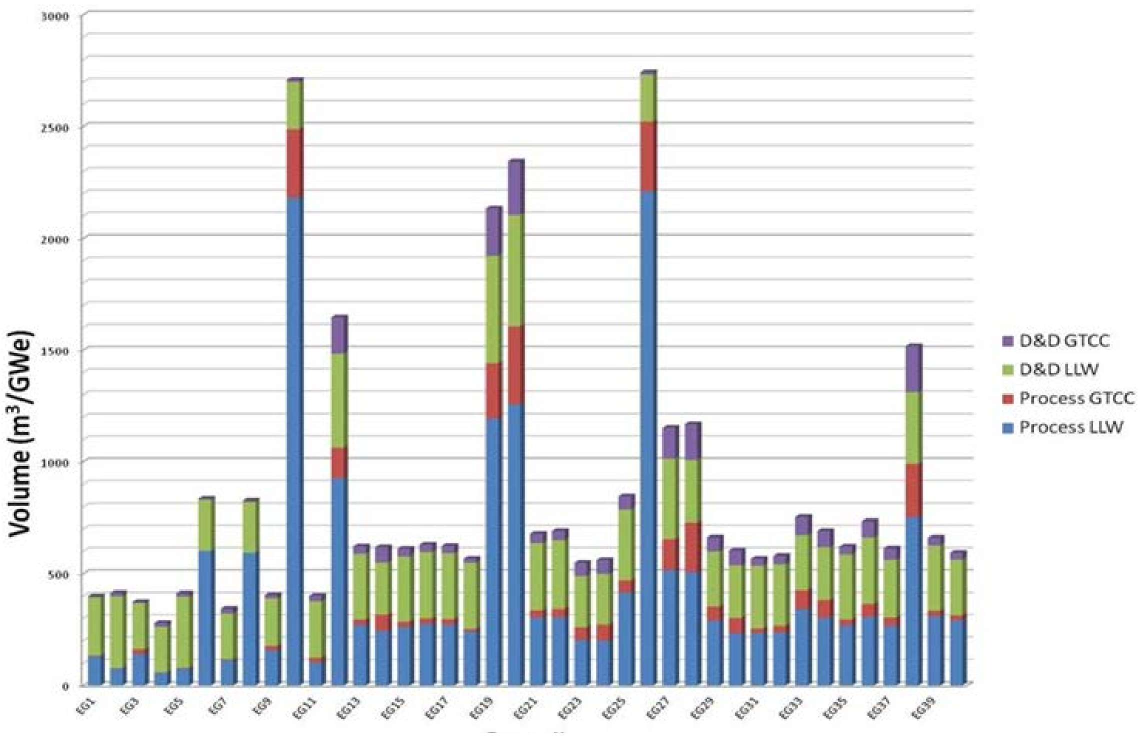


Figure D-2.5.5. Low Level Waste Type and Origin Breakdown for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

Each of the four primary operations within the fuel cycle was also examined for possible trends. Figure D-2.5.6 examines the low-level waste from enrichment operations. Two general points need to be made regarding this aspect of low-level waste generation. First, not all fuel cycles contained enrichment operations. Those not using enrichment obviously generate no waste and the resulting bar within the chart is at zero. The second point is that the volume of low-level waste is dominated by the D&D of the enrichment facility.

Figure D-2.5.7 displays the low-level waste generation associated with fuel fabrication. The two fuel cycles that result in the highest quantity of low-level waste generated are EG06 and EG08. The volume of low-level waste reflects the large volume of tritium fuel production required. This level of tritium fuel production has never been demonstrated at this scale for commercial power production. EG19, EG20 and EG28 also stand out due to the large volume of GTCC waste generated from fuel fabrication. For EG19 and EG20, this is associated with the fabrication of the MOX / TRU containing HWR fuel. For EG28, GTCC waste is associated with the fabrication of recycle Th / TRU metal fuel.

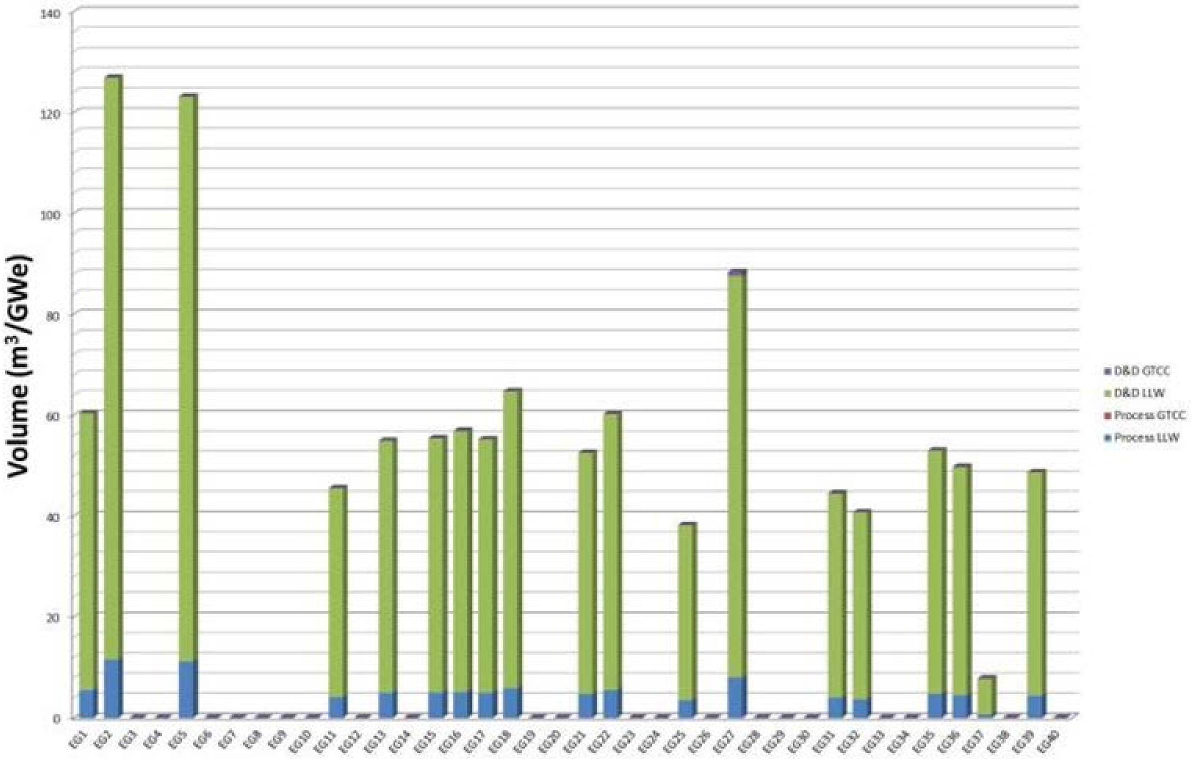


Figure D-2.5.6. LLW Generation Breakdown from Enrichment Operations for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

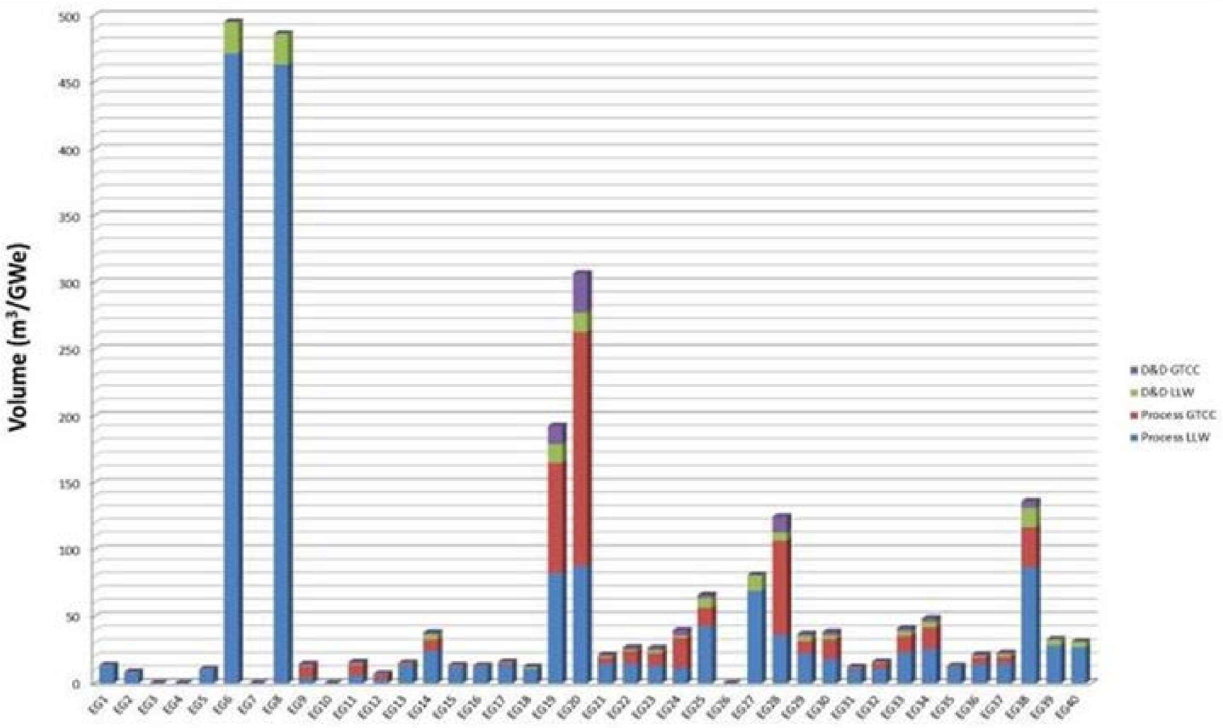


Figure D-2.5.7. LLW Generation Breakdown from Fuel Fabrication Operations for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

Figure D-2.5.8 examines the low-level waste arising from reactor operations. As noted earlier there is little variability in the volume of waste generated. Sixty to seventy percent (60 to 70%) of the low-level waste is associated with D&D operations. Only four of the Evaluation Groups show significant GTCC arising from processing operations. These are EG03, EG12, EG19, and EG20. This is associated with the operations of the HWR.

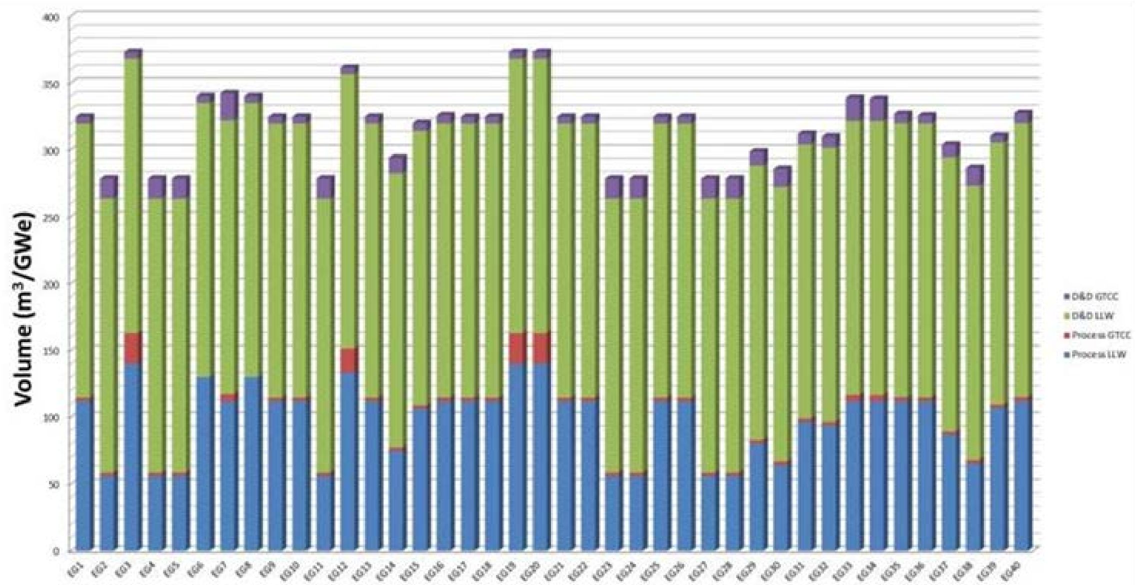


Figure D-2.5.8. LLW Generation Breakdown from Reactor Operations for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

Figure D-2.5.9 shows the volume of low-level waste arising from the reprocessing of the fuel. Obviously reprocessing is not associated with the once through Evaluation Groups and these are shown as generating zero low-level waste. The operational portion of the low-level waste dominates resulting in 60 to 80% of the total low-level waste generated. The D&D portion is relatively small compared to the processing waste. The six major bars shown on this figure have been previously discussed.

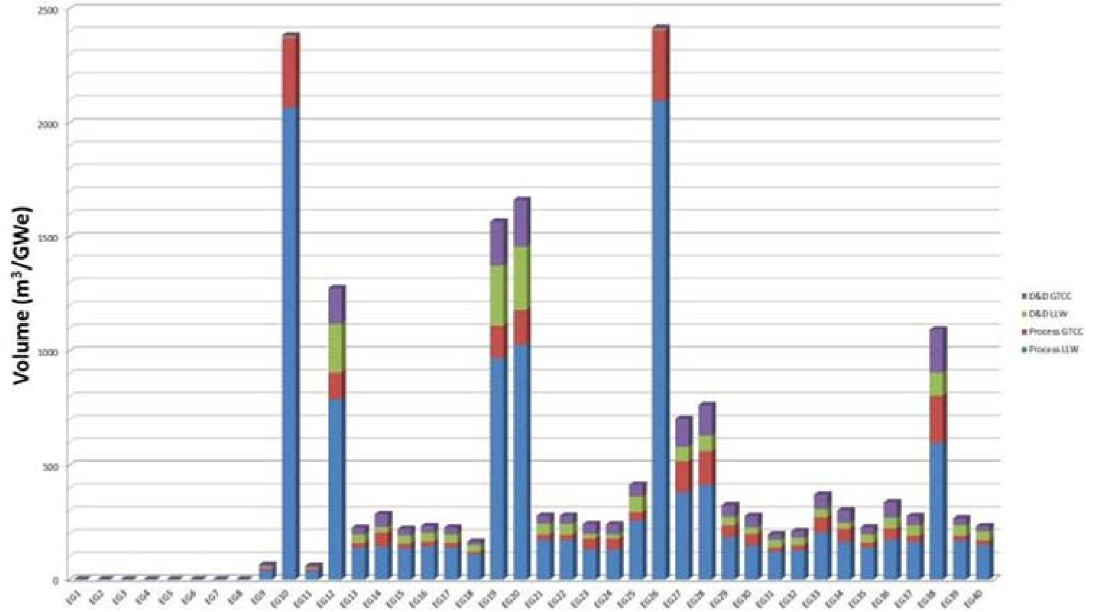


Figure D-2.5.9. LLW Generation Breakdown from Reprocessing for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups

Table D-2.5.2 contains a list of all of the Evaluation Groups and the Metric Data. If the level of improvement represented by bin A or B were considered significant, then the corresponding set of Evaluation Groups meeting or exceeding that level of improvement would be considered as promising. However neither of these bins is populated. This means that none of the Evaluation Groups reduced the volume of low-level waste generated by more than 40% from the Basis of Comparison. Bin C contained 22 of the Evaluation Groups including the Basis of Comparison (EG01). Eight of the 22 continuous recycle Evaluation Groups are contained within bin C. If the Evaluation Groups having LLW generation that is similar to that for the Basis of Comparison are viewed as being promising since LLW generation does not increase with some more complex fuel cycles, then those Evaluation Groups are in bin C and they include once-through, limited recycle, and continuous recycle options:

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

Supporting R&D and Insights

There are a number of areas where supporting R&D would potentially benefit in the reduction of low-level waste produced by the various fuel cycles examined in this study and they would apply to most if not all fuel cycles, such as R&D directed towards actual reduction in the generation of low-level waste. One example would be improved facility design with the specific intent to simplify and reduce the quantity of waste arising when the facility undergoes D&D. Another aspect of waste management is that many advanced fuel cycles have an objective to significantly reduce the volume and radiotoxicity of HLW destined for disposal. These results show that it may be possible to implement such fuel cycles without detriment to the volume of LLW generated through these additional processes. That said, R&D should also be directed to support an integrated approach to develop a cost effective, integrated approach to the management of both HLW and LLW.

Some specific examples where R&D could alter the trends in this metric are as follows, recognizing that such improvements could favorably impact many or all fuel cycles and are not considerations for comparing one fuel cycle to another. These include refinements in the reprocessing and separation operations for online processing of molten salt reactor fuel that have the potential for moving these fuel cycles to a more promising bin; i.e., moving from Bin E to Bin D or lower. Additional improvements to the scale up of tritium fuel fabrication also has the potential to reduce the estimated quantity of low-level waste produced and also move these fuel cycles from Bin E to Bin D or lower. Reactor life extensions would reduce the quantity of D&D waste from the reactor operations by spreading this over a larger amount of electrical energy production and move these fuel cycles towards or into bin B. The reduction of D&D waste through improved facility design was mentioned earlier but specifically this would be targeted to move facilities towards bin B. These improvements could come from facility life extensions or through design changes that would facilitate the eventual dismantlement of the facility. A clear example of this is the D&D of enrichment facilities where it was noted that the D&D is the major contributor to low-level waste generation from this portion of the fuel cycle.

D-2.6 Material Attractiveness - Normal Operating Conditions

Many of the Analysis Examples described in Appendix B used materials under normal operating conditions that were unattractive for proliferant activities. A review of those Analysis Examples that used potentially attractive materials indicated that in principle these fuel cycles could also be developed and implemented using unattractive materials by making different choices for the fuel cycle operating parameters such as the reactor refueling interval and the fuel burnup at discharge. Since all of the

Evaluation Groups could be implemented using unattractive materials for normal operating conditions, all of the groups had comparable material attractiveness and no promising options were identified.

D-2.7 Activity of SNF+HLW (@10 years) per Energy Generated

The spent fuel and HLW characteristics for each of the Analysis Examples indicated that in all cases, the materials were highly radioactive. Fission products dominated the activity of SNF+HLW at 10 years, with all other elements collectively contributing about 25% or less of the activity, especially when the actinide elements are recycled. The observed variations between the Analysis Examples had two main causes: (1) fission yield and (2) residence time. First, the yield of the fissile elements used in the 40 fuel cycles can be significantly different due to the use of uranium and/or thorium fuel. The fission products generated were similar but their relative amounts vary, which can impact the total activity. Second, some Analysis Examples had a fuel residence time in the reactor that was significantly longer which allowed some of the content of shorter-lived highly-radioactive fission products to decay while the fuel was still in the reactor instead of being present 10 years after discharge. Overall, the variation in activity at 10 years after discharge among all Analysis Examples from highest to lowest was about a factor of 2, with all still being highly radioactive, making the spent fuel and HLW materials in all fuel cycles a theft target of comparable use in RDDs and REDs. All of the Evaluation Groups used highly radioactive materials and no promising options were identified.

D-2.8 Challenges of Addressing Safety Hazards

Approach for determining metric data

The approach for determining the Metric Data for the challenges of addressing the safety hazards for each Evaluation Group is based on combining the data for the fuel cycle processes of which the evaluation group is composed. In Appendix C-4 data for the challenge of addressing safety hazard is provided for each fuel cycle process. Using the fuel cycle process to Evaluation Group mapping table in Appendix C-4 (Table C-4.4), the fuel cycle process data can be combined to obtain the overall metric data for the Evaluation Group. Based on the determination of hazards for each Evaluation Group the metric data bin is selected based on the following guidelines (See Table D-2.8.2 for bin definitions):

> *Bin A: Much Less Challenging:* The identified hazard categories for the evaluation group are fewer, by more than one, that the hazard categories associated with the Basis of Comparison.
>
> *Bin B: Less Challenging:* The identified hazard categories for the evaluation group are fewer, by one, than the hazard categories associated with the Basis of Comparison, or the identified hazards are similar to those in the basis of comparison but the magnitude of the hazard is judged to be less.
>
> *Bin C: Similar in Challenge:* There are no new hazard categories identified that are not present in the current U.S. nuclear fuel cycle, and the magnitude of the hazard is judged to be comparable.
>
> *Bin D: More Challenging:* There is one additional hazard category for the evaluation group that is not present in the current U.S. nuclear fuel cycle, or the identified hazards are similar but of greater magnitude, such that the hazard is judged to be potentially beyond that addressed in the current U.S. nuclear fuel cycle.
>
> *Bin E: Significantly More Challenging:* There are more than one additional hazard categories for the evaluation group than those present in the current U.S. nuclear fuel cycle. At least one of those hazards is potentially more challenging to address (i.e. there currently exists no similar or related experience

Metric data

The challenge of addressing safety hazards metric data for each Evaluation Group is provided in Table D-2.8.1 and is presented on Figure D-2.8.1. The bin descriptions for the challenge of addressing safety hazards bins in this table are defined in Appendix C-4 and are repeated in Table D-2.8.2.

Table D-2.8.1. Challenge of Addressing Safety Hazards Metric Data.

Evaluation Group	Bin Data
EG01	Bin C
EG02	Bin C
EG03	Bin C
EG04	Bin C
EG05	Bin C
EG06	Bin D
EG07	Bin D
EG08	Bin D
EG09	Bin C
EG10	Bin C
EG11	Bin C
EG12	Bin C
EG13	Bin C
EG14	Bin C
EG15	Bin C
EG16	Bin D
EG17	Bin C
EG18	Bin C
EG19	Bin C
EG20	Bin C
EG21	Bin C
EG22	Bin C
EG23	Bin C
EG24	Bin C
EG25	Bin C
EG26	Bin C
EG27	Bin C
EG28	Bin C
EG29	Bin C
EG30	Bin C
EG31	Bin C
EG32	Bin C
EG33	Bin D
EG34	Bin D
EG35	Bin D
EG36	Bin D
EG37	Bin C
EG38	Bin D
EG39	Bin D
EG40	Bin D

Table D-2.8.2. Challenge of Addressing Safety Hazards Bin Descriptions.

Bin	**Bin Description**
A: Potentially much Less Challenging that the current US nuclear fuel cycle	Identified hazards are potentially much less challenging to address than those hazards that have been encountered and addressed through past R&D and/or current and past industrial processes.
B: Potentially less Challenging than the current US nuclear fuel cycle	Identified hazards are potentially less challenging to address than those hazards that have been encountered and addressed through past R&D and/or current and past industrial processes.
C: Potentially similar in Challenge to the current US nuclear fuel cycle	Identified hazards are potentially similar in challenge to address than those hazards that have been encountered and addressed through past R&D and/or current and past industrial processes. This bin contains the Basis of Comparison
D: Potentially more Challenging than the current US nuclear fuel cycle	Identified hazards are potentially more challenging to address than those hazards that have been encountered and addressed through past R&D and/or current and past industrial processes.
E: Potentially significantly More Challenging than the current US nuclear fuel cycle	Identified hazards are potentially significantly more challenging to address than those hazards that have been encountered and addressed through past R&D and/or current and past industrial processes.

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.8.1 (note that the same data is provided in the second column of Table D-2.8.1) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

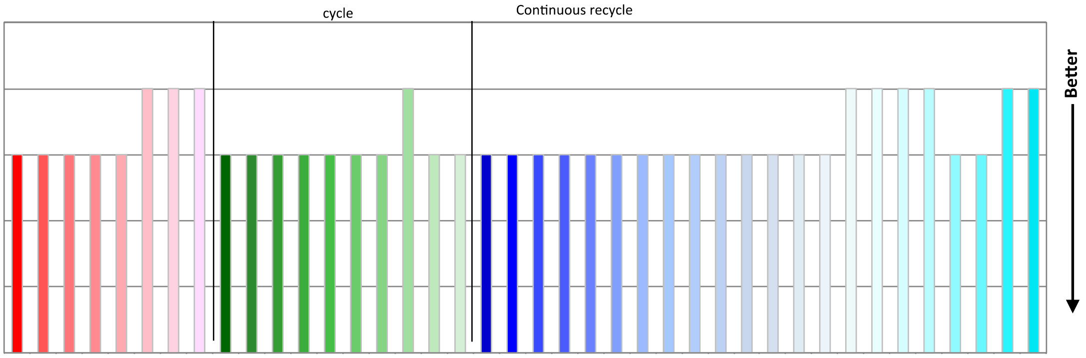


Figure D-2.8.1. Metric Data for the Challenges of Addressing Safety Hazards for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Options

For the challenge of addressing safety hazards metric, no Evaluation Groups were found to have performance that exceeded that of the Basis of Comparison (EG01) and therefore no promising Evaluation Groups were identified. However, based on a ranking of the Evaluation Groups by bin, observations of the Evaluation Groups are as follows:

- All fuel cycle Evaluation Groups except those using EDSs have similar challenges to addressing safety hazards as the basis for comparison based on a review of a range of hazard categories and previous industry and research experience with those hazards.

- EDSs have additional challenges that must be addressed associated with the use of the external neutron source and its coupling with the blanket system. This includes challenges related to handling of large amounts of tritium, worker dose issues related to the operation of the system and coupling between the neutron source and blanket, and safety case for EDSs that operate in subcritical mode including new potential events related to source excursions and reactivity feedback.
- While the results for this metric indicate a similar level of challenge for most Evaluation Groups at the fuel cycle level, this does not imply potential for improvement to safety, which must be considered by choices and improvements to the specific technologies used in a particular fuel cycle and not at the fuel cycle level itself. This is the goal of U.S. and international nuclear energy R&D programs, including Generation-IV.

Supporting R&D and Insights

The ability to design, deploy, and operate all nuclear facilities safely is a requisite for any fuel cycle. R&D on any technology should always have safety considerations as one of the key aspects, along with all of the performance-driven requirements.

D-2.9 Safety of the Deployed System

Approach for determining metric data

The approach for determining the safety of the deployed system metric data for each Evaluation Group uses an approach based an assessment of data for the fuel cycle processes that the evaluation group is composed. In Appendix C-4 the fuel cycle process data for the safety of the deployed system is discussed with the process data determined by reviewing the data for the challenges of addressing safety hazards data and for those processes determined to be more challenging a determination if the hazards that are considered to be more challenging can be addressed. The metric data for each fuel cycle process and the fuel cycle process to Evaluation Group mapping table in Appendix C-4 (Table C-4.4) along with the determination from the challenge of addressing safety hazards metric will identify any Evaluation Group that have hazards that cannot be addressed. In that situation, the Evaluation Group Metric Data will show that the Evaluation Group cannot be deployed safely.

Metric data

All Evaluation Groups were determined to be able to be deployed safely. The metric data for each Evaluation Group is provided in Table D-2.9.1 is presented in Figure D-2.9.1.

Table D-2.9.1. Challenge of Addressing Safety Hazards Metric Data.

Evaluation Group	Metric Data
EG01	Can be deployed safely
EG02	Can be deployed safely
EG03	Can be deployed safely
EG04	Can be deployed safely
EG05	Can be deployed safely
EG06	Can be deployed safely
EG07	Can be deployed safely
EG08	Can be deployed safely
EG09	Can be deployed safely
EG10	Can be deployed safely
EG11	Can be deployed safely
EG12	Can be deployed safely
EG13	Can be deployed safely
EG14	Can be deployed safely

EG15	Can be deployed safely
EG16	Can be deployed safely
EG17	Can be deployed safely
EG18	Can be deployed safely
EG19	Can be deployed safely
EG20	Can be deployed safely
EG21	Can be deployed safely
EG22	Can be deployed safely
EG23	Can be deployed safely
EG24	Can be deployed safely
EG25	Can be deployed safely
EG26	Can be deployed safely
EG27	Can be deployed safely
EG28	Can be deployed safely
EG29	Can be deployed safely
EG30	Can be deployed safely
EG31	Can be deployed safely
EG32	Can be deployed safely
EG33	Can be deployed safely
EG34	Can be deployed safely
EG35	Can be deployed safely
EG36	Can be deployed safely
EG37	Can be deployed safely
EG38	Can be deployed safely
EG39	Can be deployed safely
EG40	Can be deployed safely

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.9.1 (note that the same data is provided in the second column of Table D-2.9.1) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

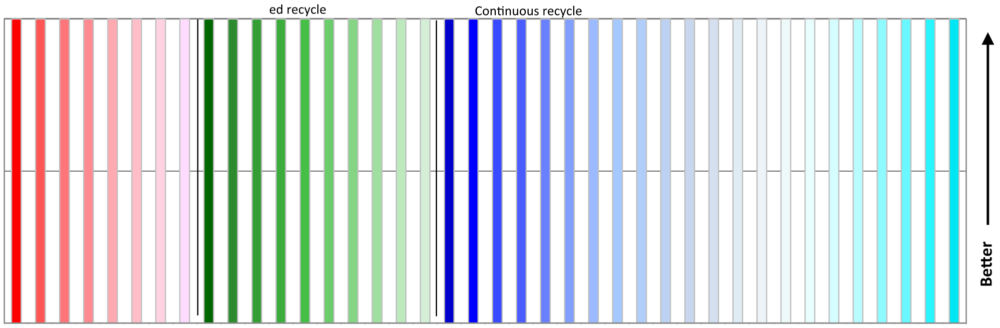


Figure D-2.9.1. Metric Data for the Safety of the Deployed System for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Options

For the safety of the deployed system, all Evaluation Groups were found to be able to be deployed safely. Based on the nature of this metric, no promising Evaluation Groups can be identified. There were no fuel cycle Evaluation Groups that had safety challenges that could not be addressed including the EDSs, which will require additional R&D to address those items identified in the Challenges to Addressing Safety Hazards Metric. As noted above, the potential for safety improvements should be considered in the selection and development of the specific technologies used for implementing a particular fuel cycle.

Supporting R&D and Insights

As with the previous metric, the ability to design, deploy, and operate all nuclear facilities safely is a requisite for any fuel cycle. R&D on any technology should always have safety considerations as one of the key aspects, along with all of the performance-driven requirements.

D-2.10 Land Use per Energy Generated

As described in Appendix C-5.3, the Land Use per Energy Generated of the 40 Evaluation Groups was calculated using the specific information that was developed for each Evaluation Group Analysis Example using the impact factors or multipliers for each of the appropriate fuel cycle operations. The land use estimates from the Analysis Examples are shown in on Figure D-2.10.1. These estimates were then distributed into a 5-bin structure that was developed to identify fuel cycles that could achieve a significant degree of change from the Basis of Comparison. The land usage for the Basis of Comparison (EG01) is 0.175 km^2 / GWe-y (see Appendix C-5.3 for details).

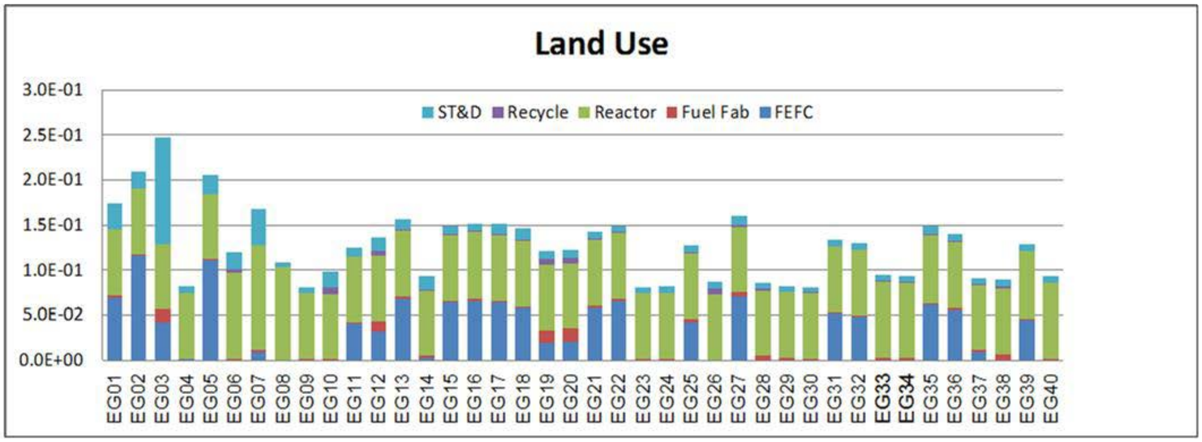


Figure D-2.10.1. Land Use for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

A five bin binning structure was established that divided the range of land usage into five unequal bins in the sense of span of area. The selected bin ranges were <0.1, 0.1 – 0.2, 0.2 – 0.5, 0.5 – 1.0, and > 1.0 km^2/GWe-y. The bin structure is presented in Table D-2.10-1. The bin boundaries are shown overlaid on the calculated land usage estimates from the Analysis Examples in Figure D-2.10.2. Bin "A" contains the smallest amount of land use and Bin "E" represents the largest amount of land use. Bins "D" and "E" are not populated. It is easily observed from this figure that most of the Evaluation Groups are either in bins "A" or "B." Only three Evaluation Groups lie in bin "C" (EG02 - Once-through U to high burnup in thermal critical reactor with enrichment, EG03 - Once-through U thermal critical reactor without enrichment, EG05 - Once-through U/Th in thermal critical reactor with enrichment) and that these are all once-through options. EG02 and EG05 have relatively large land usages in the front end of the fuel cycle and EG03 has a large land usage in the Storage, Transportation and Disposal portion of the fuel cycle. Note that the Basis of Comparison lies in Bin "B".

Table D-2.10.1. Metric Bins for Land Use per Energy Generated.

Bin ID	**Data Range (km^2/GWe-yr)**	**Bin Description**
A	< 0.1	Land use per energy generated < 0.1 km^2/GWe-yr
B	0.1 to < 0,2	Land use per energy generated ≥ 0.1 km^2/GWe-yr and < 0.2 km^2/GWe-yr; this bin contains the Basis of Comparison
C	0.2 to < 0.5	Land use per energy generated ≥ 0.2 km^2/GWe-yr and < 0.5 km^2/GWe-yr
D	0.5 to < 1.0	Land use per energy generated ≥ 0.5 km^2/GWe-yr and < 1.0 km^2/GWe-yr
E	≥ 1.0	Land use per energy generated ≥ 1.0 km^2GWe-yr

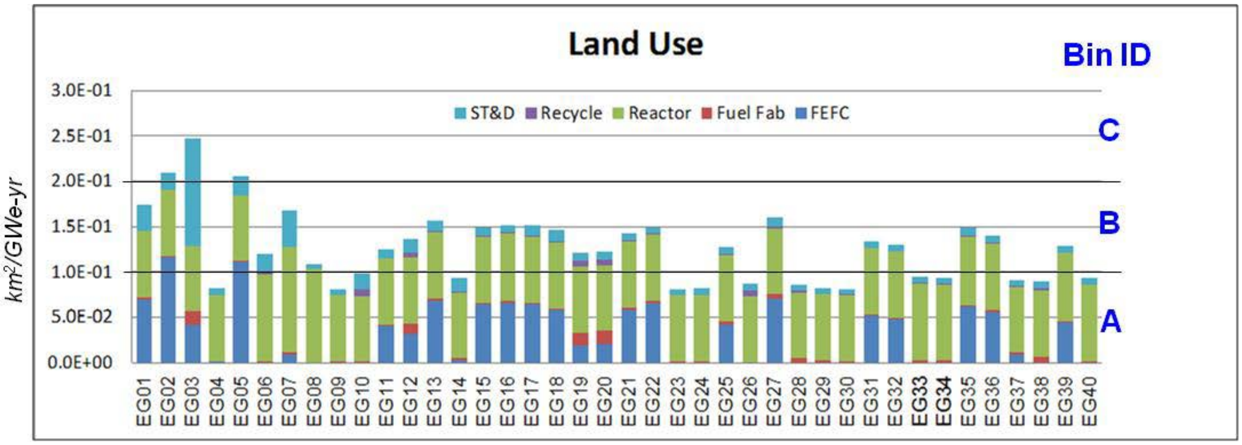


Figure D-2.10.2. Overlay of Bins on Land Use Estimates for the Analysis Example for the 40 Evaluation Groups.

Description of Metric Data

As previously noted, the land use for each of the Analysis Examples was developed for each Evaluation Group using the methodology described in Appendix C-5.3. The Metric Data is the bin assignment. This assignment is shown on Table D-2.10.2. Based on the calculated land usage for the Analysis Example each Evaluation Group was assigned to an appropriate bin. This bin assignment was reviewed by considering each of the fuel cycle options contained within the Evaluation Group. Based on this analysis no re-assignment of bins was necessary.

Table D-2.10.2. Land Use Metric Data for the Evaluation Groups.

Evaluation Group	Land Use for Analysis Example (km^2/GWe-yr)	Metric Data	Metric Data Bin Boundaries
EG01	0.175	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG02	0.210	C	≥ 0.2 km^2/GWe-yr to < 0.5 km^2/GWe-yr
EG03	0.247	C	≥ 0.2 km^2/GWe-yr to < 0.5 km^2/GWe-yr
EG04	0.082	A	< 0.1 km^2/GWe-yr

EG05	0.206	C	≥ 0.2 km^2/GWe-yr to < 0.5 km^2/GWe-yr
EG06	0.119	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG07	0.167	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG08	0.109	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG09	0.081	A	< 0.1 km^2/GWe-yr
EG10	0.098	A	< 0.1 km^2/GWe-yr
EG11	0.126	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG12	0.137	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG13	0.156	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG14	0.094	A	< 0.1 km^2/GWe-yr
EG15	0.149	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG16	0.152	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG17	0.151	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG18	0.147	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG19	0.121	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG20	0.123	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG21	0.143	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG22	0.150	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG23	0.081	A	< 0.1 km^2/GWe-yr
EG24	0.082	A	< 0.1 km^2/GWe-yr
EG25	0.128	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG26	0.086	A	< 0.1 km^2/GWe-yr
EG27	0.160	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG28	0.086	A	< 0.1 km^2/GWe-yr
EG29	0.083	A	< 0.1 km^2/GWe-yr
EG30	0.081	A	< 0.1 km^2/GWe-yr
EG31	0.134	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG32	0.130	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG33	0.095	A	< 0.1 km^2/GWe-yr
EG34	0.093	A	< 0.1 km^2/GWe-yr
EG35	0.149	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG36	0.140	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG37	0.091	A	< 0.1 km^2/GWe-yr
EG38	0.090	A	< 0.1 km^2/GWe-yr
EG39	0.130	B	≥ 0.1 km^2/GWe-yr to < 0.2 km^2/GWe-yr
EG40	0.094	A	< 0.1 km^2/GWe-yr

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.10.3 (note that the same data is provided in the third column of Table D-2.10.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

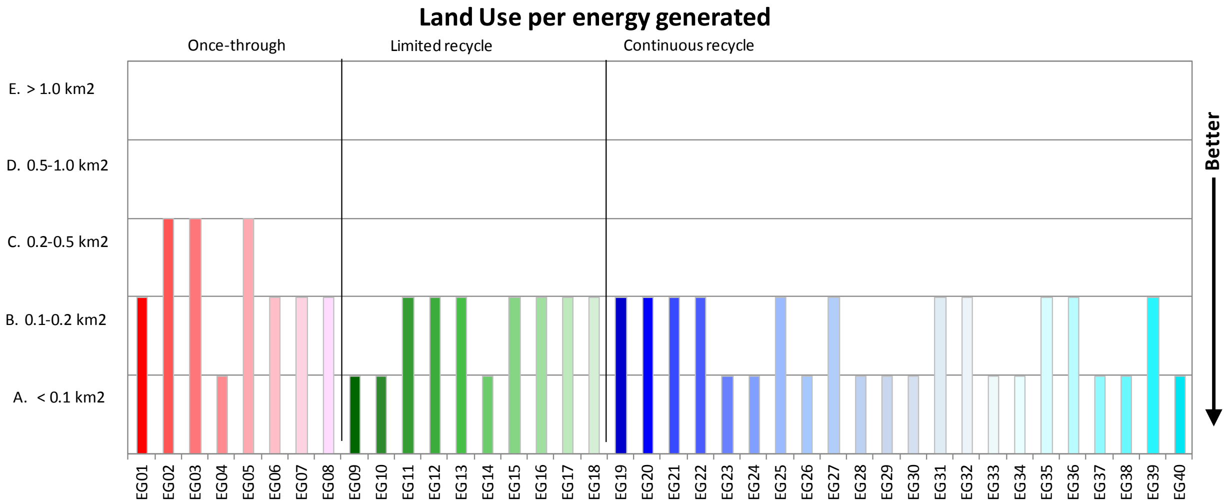


Figure D-2.10.3. Metric Data for Land Use for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups

Table D-2.10.2 provides a list of all of the Evaluation Groups and the Metric Data. The Basis of Comparison is in bin B. If the improvements represented by bin A were considered significant, then the promising Evaluation Groups would be found within this bin. A common trait among the Evaluation Groups in bin A is high resource utilization and low values for SNF/HLW masses. The largest variations in fuel cycle element contributions were the front end of the fuel cycle and the back end of the fuel cycle. The variation in the land usage for reactors, fuel fabrication, and recycle components were relatively small.

Bin A < 0.1 km^2/GWe-yr	EG04, EG09, EG10, EG14, EG23, EG24, EG26, EG28, EG29, EG30, EG34, EG37, EG38, EG40

Supporting R&D, and Insights

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

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

D-2.11 Water Use per Energy Generated

As described in Appendix C-5.4, the water use for each of the 40 Evaluation Groups was calculated using the information that was developed for each of the Analysis Example for each Evaluation Group and the impact factors or multipliers for each of the appropriate fuel cycle operations. The calculated raw water use estimates for the Analysis Examples are shown in Figure D-2.11.1. These values were then assigned into a 3 bin structure that was developed in such a way as to identify fuel cycles that could achieve a significant degree of change from the basis of comparison. The Screening and Evaluation team working on this metric initially assumed that the probable range of values would be between 10,000 and 30,000 ML / GWe-y. After completing the calculation of the entire set of water use values for the 40 Analysis Examples it was observed that the actual range was slightly different – 23,700 to ~ 38,000 ML/GWe-y. The water usage for the basis of comparison (EG01 - once-through thermal critical reactor using enriched uranium) is 23,893 ML/GWe-y (see Appendix C-5.4 for details).

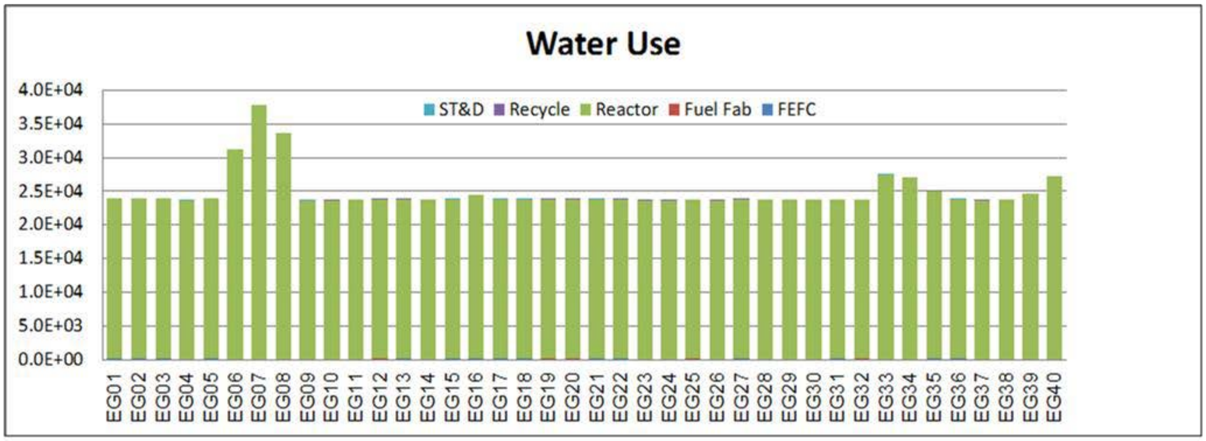


Figure D-2.11.1. Water Use for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group.

A three bin binning structure was established that divided the range of water usage. The selected bin ranges were < 15,000, 15,000 - <30,000, > 30,000 ML / GWe-y. The bin structure is presented in Table D-2.11.1. The bin boundaries are shown overlaid on the calculated water usage estimates from the Analysis Examples in Figure D-2.11-2. Bin "A" contains the smallest amount of water use and Bin "C" represents the largest amount of water use. Bin "A" is not populated. It is easily observed from this figure that most of the Evaluation Groups are in bin "B."

Table D-2.11.1. Metric Bins for Water Use per Energy Generated.

Bin ID	Data Range (ML/GWe-yr)	Bin Description
A	< 15,000	Water use per energy generated < 15,000 ML/GWe-yr
B	15,000 to < 30,000	Water use per energy generated ≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr; this bin contains the Basis of Comparison
C	≥ 30,000	Water use per energy generated ≥ 30,000 ML/GWe-yr

Note: 1 ML = 10^6 liters.

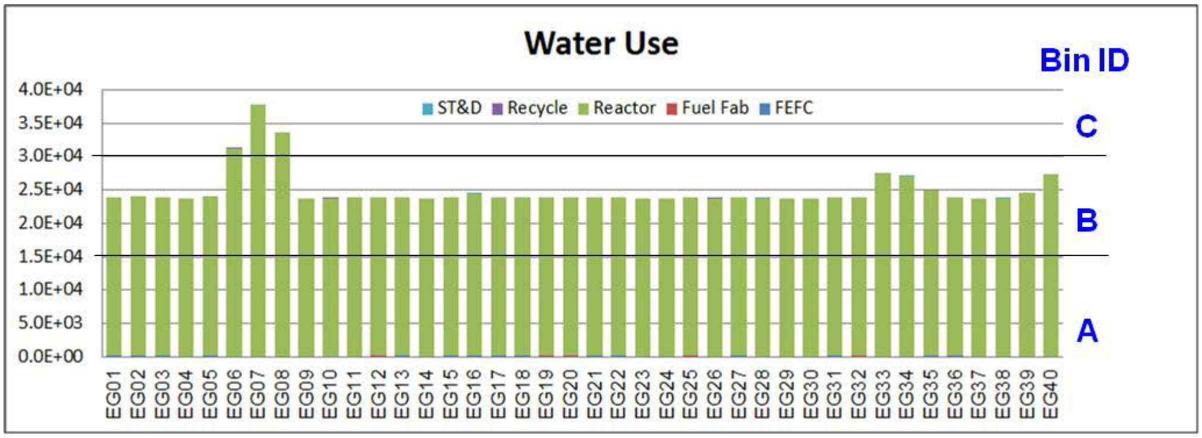


Figure D-2.11.2. Overlay of Bins on Water Use Estimates for the Analysis Example for Each Evaluation Group.

Only three Evaluation Groups lie in bin “C” (EG06, EG07, and EG08) and that these are all once-through options that are exclusively EDS systems that require significant additional cooling for the extra energy used by the neutron generator. EDS are also contained within other EG’s for a small portion of the system but the contribution is not enough to drive these to the next higher bin. It can also be seen in this figure that the reactor component dominates the water usage. Also note that the Basis of Comparison lies in Bin “B” and that none of the EG’s had better performance in terms of water usage.

Using these bin boundaries, the data from the Analysis Examples is placed into the appropriate bin and is the Metric Data for the Evaluation Group, as listed in Table D-2.11.2.

Table D-2.11.2. Water Use Metric Data for the Evaluation Groups.

Evaluation Group	Water Use for Analysis Example (ML/GWe-yr)	Metric Data	Metric Data Bin Boundaries
EG01	23891	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG02	23994	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG03	23924	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG04	23706	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG05	23981	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG06	31308	C	≥ 30,000 ML/GWe-yr
EG07	37831	C	≥ 30,000 ML/GWe-yr
EG08	33640	C	≥ 30,000 ML/GWe-yr
EG09	23709	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG10	23767	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG11	23810	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG12	23912	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG13	23897	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG14	23728	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG15	23881	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG16	24495	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG17	23883	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG18	23861	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG19	23897	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG20	23909	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG21	23874	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG22	23891	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG23	23717	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr

EG24	23717	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG25	23839	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG26	23762	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG27	23909	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG28	23748	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG29	23725	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG30	23719	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG31	23847	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG32	23838	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG33	27521	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG34	27104	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG35	24957	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG36	23887	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG37	23717	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG38	23770	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG39	24623	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr
EG40	27306	B	≥ 15,000 ML/GWe-yr and < 30,000 ML/GWe-yr

Description of Metric Data

As previously noted, the water use for each of the Analysis Examples was developed for each Evaluation Group using the methodology described in Appendix C-5.4. The Metric Data is the bin assignment as listed in Table 2.11.2. Based on the calculated water usage for the Analysis Example each Evaluation Group was assigned to an appropriate bin. This bin assignment was reviewed by considering each of the fuel cycle options contained within the Evaluation Group. Based on this analysis no re-assignment of bins was necessary.

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.11.3 (note that the same data is provided in the third column of Table D-2.11.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

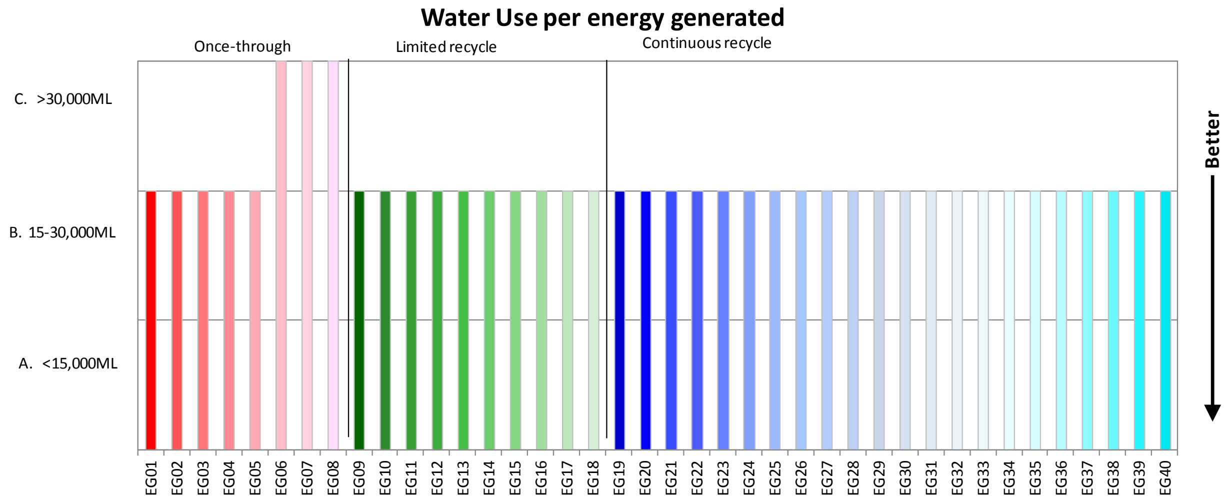


Figure D-2.11.3. Metric Data for Water Use for the Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups

Table D-2.11.2 provides a list of all of the Evaluation Groups and the Metric Data by bin. The Basis of Comparison is in bin B. If the improvements represented by bin A were considered significant, then the promising Evaluation Groups would be found within this bin. However there are no Evaluation Groups that appear to have the potential to provide improvement in the water use required over the basis of comparison. The EDS systems are estimated to require more water due to the additional water used by the external driver. The Evaluation Groups in bin B indicate those fuel cycles that can be implemented without increasing water use as compared to the current U.S. fuel cycle.

Supporting R&D, and Insights

Based on that there are no identified Evaluation Groups that appear to have the potential to provide improvement in the water use required over the Basis of Comparison, arising from the conditional statements on promising options, no recommendations on R&D activities that would enable the deployment and better performance of the Evaluation Groups will be made.

D-2.12 Carbon Emission - CO_2 Released per Energy Generated

As described in Appendix C-5.5, the carbon emissions in terms of CO_2 released per unit of energy for each of the 40 Evaluation Groups was calculated using the information that was developed for each of the Analysis Examples and the impact factors or multipliers for each of the appropriate fuel cycle operations. The carbon emissions data from the Analysis Examples is shown in Figure D-2.12.1. These values were translated into a bin structure that was developed to identify fuel cycles that could achieve a significant degree of change from the Basis of Comparison. The EST working on this metric initially assumed that the probable range of values would be between 200,000 and 600,000 t CO_2/GWe-y. After completing the calculation of the entire set of CO_2 released per unit of energy values for the 40 Analysis Examples it was observed that the actual range was from about 12,200 to 158,000 t CO_2/GWe-y. The carbon emissions for the Basis of Comparison (EG01- once-through thermal critical reactor using enriched uranium) are 44,000 t CO_2/GWe-y, or 5.02 g/kWh (see Appendix C-5.5 for details).

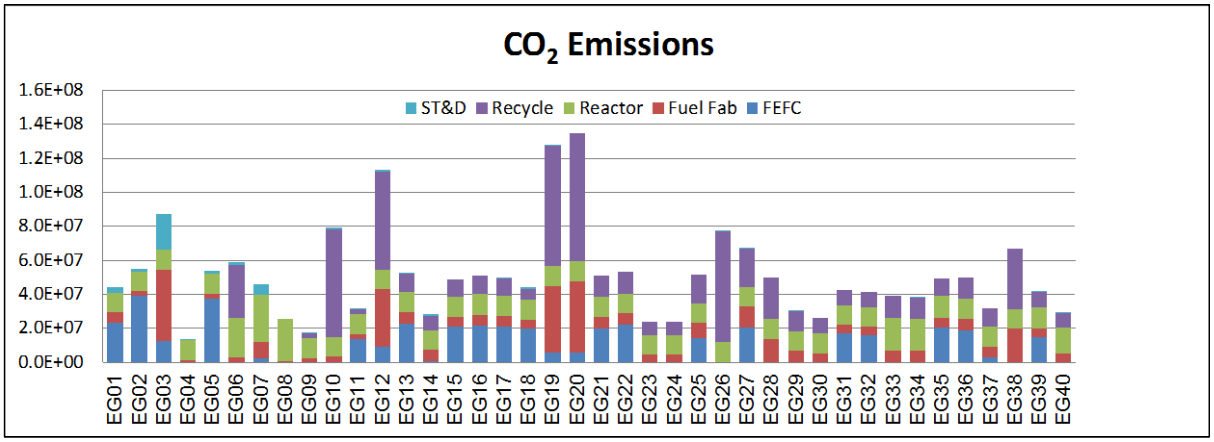


Figure D-2.12.1. Mass of Carbon Emissions for the Analysis Examples Ordered by Evaluation Group Number.

A five bin binning structure was established that divided the range of CO_2 emissions. The selected bin ranges were < 30, 30 to ≤ 60, 60 to ≤ 120, 120 to ≤ 240, and > 240 kt CO_2/GWe-y. The bin structure is presented in Table D-2.12-1. The bin boundaries are shown overlaid on the data from the Analysis

Examples in Figure D-2.12-2. Bin A contains the smallest amount of CO_2 released and Bin E represents the largest amount of CO_2 emissions. Bin E is not populated. Also note that the Basis of Comparison lies in Bin B and that several of the EG's had better performance in terms of CO_2 emissions.

Table D-2.12.1. Metric Bins for Carbon Emission - CO_2 Released per Energy Generated.

Bin ID	**Data Range (kt CO_2/GWe-yr)**	**Bin Description**
A	< 30	Carbon Emission - CO_2 Released per Energy Generated < 30 kt CO_2/GWe-yr
B	30 to < 60	Carbon Emission - CO_2 Released per Energy Generated ≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr; this bin contains the Basis of Comparison
C	60 to < 120	Carbon Emission - CO_2 Released per Energy Generated ≥ 60 kt CO_2/GWe-yr and < 120 kt CO_2/GWe-yr
D	120 to < 240	Carbon Emission - CO_2 Released per Energy Generated ≥ 120 kt CO_2/GWe-yr and < 240.0 kt CO_2/GWe-yr
E	≥ 240[2]	Carbon Emission - CO_2 Released per Energy Generated ≥ 240 kt CO_2GWe-yr

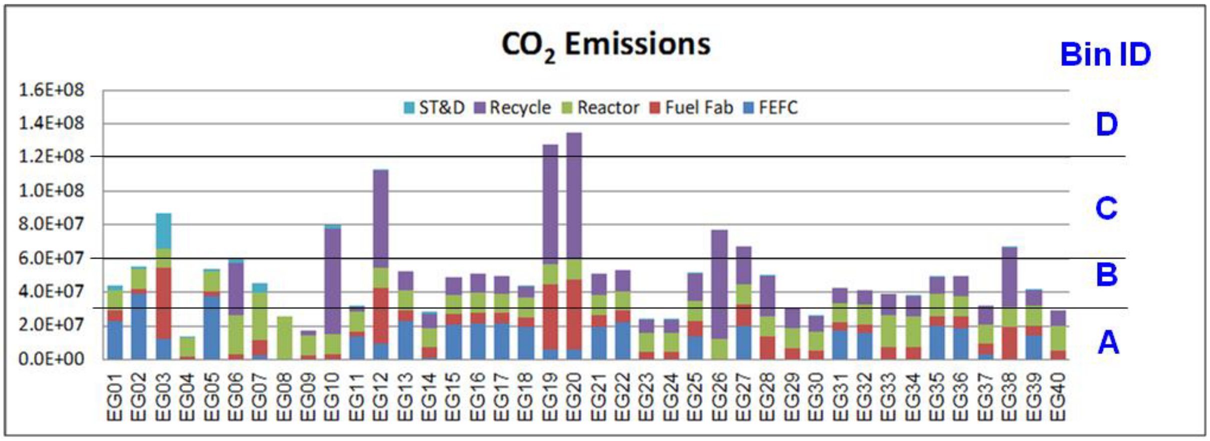


Figure D-2.12.2. Overlay of Bins on Land Use Estimates for the Analysis Example for Each Evaluation Group Ordered by Evaluation Group Number.

Using these bin boundaries, the data from the Analysis Examples is placed into the appropriate bin and is the Metric Data for the Evaluation Group, as listed in Table D-2.12.2.

Table D-2.12.2. CO_2 Released per Energy Generated Metric Data for the Evaluation Groups.

Evaluation Group	Carbon emissions for Analysis Example (kt CO_2/GWe-yr)	Metric Data	Metric Data Bin Boundaries
EG01	44.1	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG02	54.9	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG03	87.1	C	≥ 60 kt CO_2/GWe-yr and < 120 kt CO_2/GWe-yr
EG04	13.5	A	< 30 kt CO_2/GWe-yr
EG05	53.9	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG06	59.1	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG07	45.7	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr

EG08	25.4	A	< 30 kt CO_2/GWe-yr
EG09	17.5	A	< 30 kt CO_2/GWe-yr
EG10	79.5	C	≥ 60 kt CO_2/GWe-yr and < 120 kt CO_2/GWe-yr
EG11	31.8	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG12	113.3	C	≥ 60 kt CO_2/GWe-yr and < 120 kt CO_2/GWe-yr
EG13	52.7	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG14	28.5	A	< 30 kt CO_2/GWe-yr
EG15	48.8	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG16	50.9	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG17	49.9	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG18	43.9	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG19	127.9	D	≥ 120 kt CO_2/GWe-yr and < 240 kt CO_2/GWe-yr
EG20	134.9	D	≥ 120 kt CO_2/GWe-yr and < 240 kt CO_2/GWe-yr
EG21	51.1	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/We-yr
EG22	53.3	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG23	24.1	A	< 30 kt CO_2/GWe-yr
EG24	24.1	A	< 30 kt CO_2/GWe-yr
EG25	51.5	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG26	77.3	C	≥ 60 kt CO_2/GWe-yr and < 120 kt CO_2/GWe-yr
EG27	67.3	C	≥ 60 kt CO_2/GWe-yr and < 120 kt CO_2/GWe-yr
EG28	50.1	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG29	30.5	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG30	26.1	A	< 30 kt CO_2/GWe-yr
EG31	42.7	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG32	41.6	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG33	39.1	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG34	38.2	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG35	49.5	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG36	49.7	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG37	31.9	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG38	67.0	C	≥ 60 kt CO_2/GWe-yr and < 120 kt CO_2/GWe-yr
EG39	41.7	B	≥ 30 kt CO_2/GWe-yr and < 60 kt CO_2/GWe-yr
EG40	29.4	A	< 30 kt CO_2/GWe-yr

Description of Metric Data

As previously noted, the estimated carbon emissions for each of the Analysis Examples was developed for each Evaluation Group using the methodology described in Appendix C-5.5. The Metric Data is the bin assignment. This assignment is shown in the third column of Table D-2.12.2. Based on the calculated carbon emissions for the Analysis Example each Evaluation Group was assigned to an appropriate bin. This bin assignment was reviewed by considering each of the fuel cycle options contained within the Evaluation Group. Based on this analysis no re-assignment of bins was necessary.

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.12.3 (note that the same data is provided in the third column of Table D-2.12.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

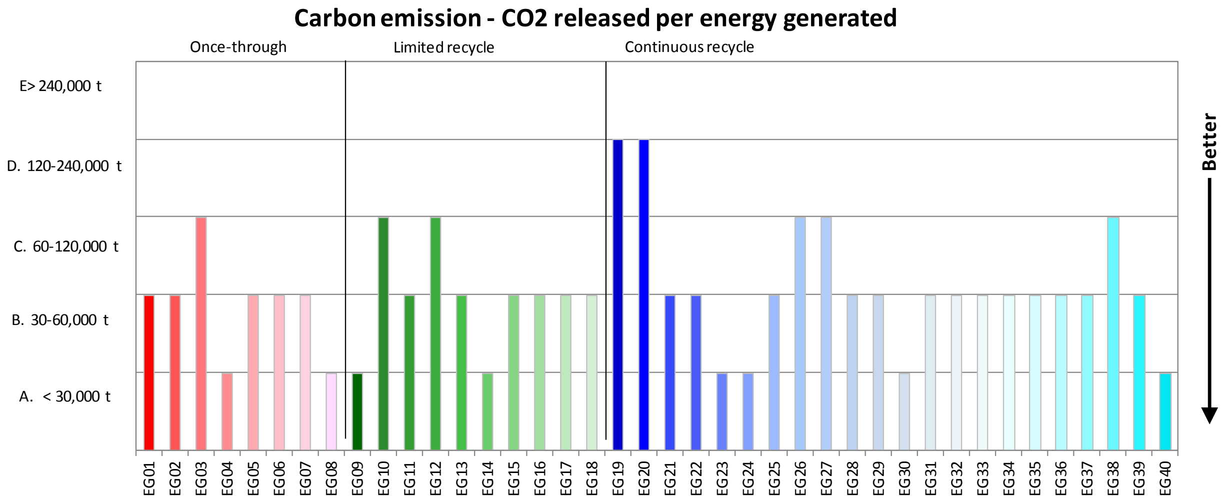


Figure D-2.12.3. Metric Data for CO_2 Emissions for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups

Table D-2.12.2 provides a list of the Metric Data for all of the Evaluation Groups. If the improvements represented by bin A were considered significant then the promising Evaluation Groups would be found within this bin.

Bin A < 30 kt CO_2/GWe-yr	EG04, EG08, EG09, EG14, EG23, EG24, EG30, EG40

Supporting R&D, and Insights

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

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

D-2.13 Radiological Exposure - Total Estimated Worker Dose per Energy Generated (as Leading Indicator for Public Dose Potential)

As described in Appendix C-5.6, the Radiological Exposure - Total Estimated Worker Dose per Energy Generated (as Leading Indicator for Public Dose Potential) for each of the 40 Evaluation Groups was calculated using the information that was developed for each of the Analysis Example for each Evaluation Group and the impact factors or multipliers for each of the appropriate fuel cycle operations. The Worker Dose estimates from the Analysis Examples are shown in Figure D-2.13.1. These values were then assigned into a bin structure that was developed in such a way as to identify fuel cycles that could achieve a significant degree of change from the basis of comparison. The Screening and Evaluation team working on this metric initially assumed that the probable range of values would be between 0 and 10 person-Sv / GWe-y. After completing the calculation of the entire set of estimated worker dose values for the 40 Analysis Examples it was observed that the actual range was from about 0.55 to 4.54 person-Sv / GWe-y. The estimated worker dose for the Basis of Comparison is 1.1 person-Sv / GWe-y (see section C-5.6 for details).

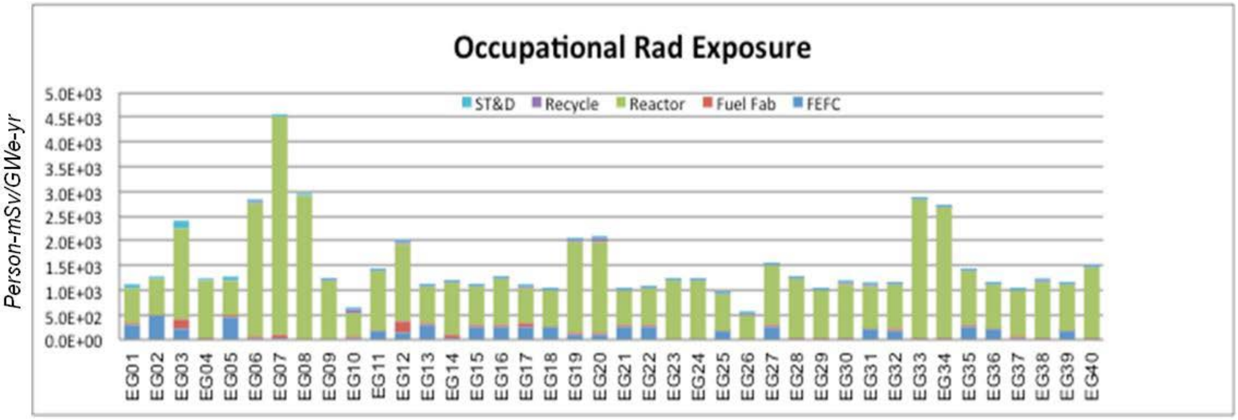


Figure D-2.13.1. Occupational Radiation Exposure for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

A three bin binning structure was established that divided the range of occupational radiation exposure. The selected bin ranges were < 0.5, 0.5 to ≤ 5.0, and > 5.0 person-Sv / GWe-y. The bin structure is presented in Table D-2.13-1. The bin boundaries are shown overlaid on the data from the Analysis Examples in Figure D-2.13.2. Bin A contains the smallest worker doses and Bin C represents the largest worker doses. All Evaluation Groups are in bin B. It can also be seen in this figure that the reactor component dominates the worker dose.

Table D-2.13.1. Metric Bins for Radiological Exposure - Total Estimated Worker Dose per Energy Generated (as Leading Indicator for Public Dose Potential).

Bin ID	Data Range (person-Sv /GWe-yr)	Bin Description
A	< 0.5	Radiological Exposure - Total Estimated Worker Dose per Energy Generated (as Leading Indicator for Public Dose Potential) < 0.5 person-Sv/GWe-yr
B	0.5 to < 5.0	Radiological Exposure - Total Estimated Worker Dose per Energy Generated (as Leading Indicator for Public Dose Potential) ≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr; this bin contains the Basis of Comparison
C	≥ 5.0	Radiological Exposure - Total Estimated Worker Dose per Energy Generated (as Leading Indicator for Public Dose Potential) ≥ 5.0 person-Sv/GWe-yr

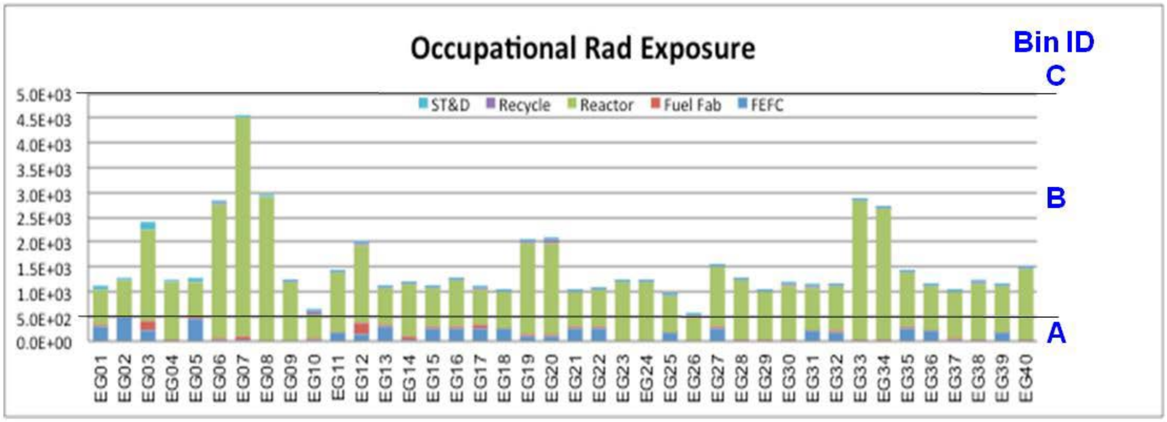


Figure D-2.13.2. Overlay of Bins on Occupational Radiation Exposure Estimates for the Analysis Example for Each Evaluation Group Ordered by Evaluation Group Number.

Also note that the Basis of Comparison lies in bin B and that none of the Evaluation Groups had better performance in terms of worker dose. Using these bin boundaries, the data from the Analysis Examples were placed into the appropriate bin and are the Metric Data for the Evaluation Group, as listed in Table D-2.13.2.

Table D-2.13.2. Radiological Exposure - Total Estimated Worker Dose per Energy Generated (as Leading Indicator for Public Dose Potential) Metric Data for the Evaluation Groups.

Evaluation Group	Radiological Impact for Analysis Example (person-mSv/GWe-yr)	Metric Data	Metric Data Bin Boundaries
EG01	1.10	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG02	1.28	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG03	2.41	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG04	1.22	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG05	1.27	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG06	2.81	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG07	4.54	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG08	2.93	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG09	1.21	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG10	0.61	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG11	1.40	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG12	2.02	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG13	1.12	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG14	1.18	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG15	1.12	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG16	1.26	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG17	1.10	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG18	1.04	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG19	2.04	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG20	2.06	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG21	1.05	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG22	1.08	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG23	1.21	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG24	1.21	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG25	0.95	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG26	0.55	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG27	1.54	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr

EG28	1.24	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG29	1.02	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG30	1.14	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG31	1.13	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG32	1.13	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG33	2.84	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG34	2.70	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG35	1.43	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG36	1.14	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG37	1.01	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG38	1.18	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG39	1.14	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr
EG40	1.49	B	≥ 0.5 person-Sv/GWe-yr and < 5.0 person-Sv/GWe-yr

Description of Metric Data

As previously noted, the worker dose for each of the Analysis Examples was developed for each Evaluation Group using the methodology described in appendix C-5.6. The Metric Data is the bin assignment. This assignment is shown in the third column of Table D-2.13.2. Based on the calculated worker dose for the Analysis Example each Evaluation Group was assigned to an appropriate bin. This bin assignment was reviewed by considering each of the fuel cycle options contained within the Evaluation Group. Based on this analysis no re-assignment of bins was necessary.

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.13.3 (note that the same data is provided in the third column of Table D-2.13.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

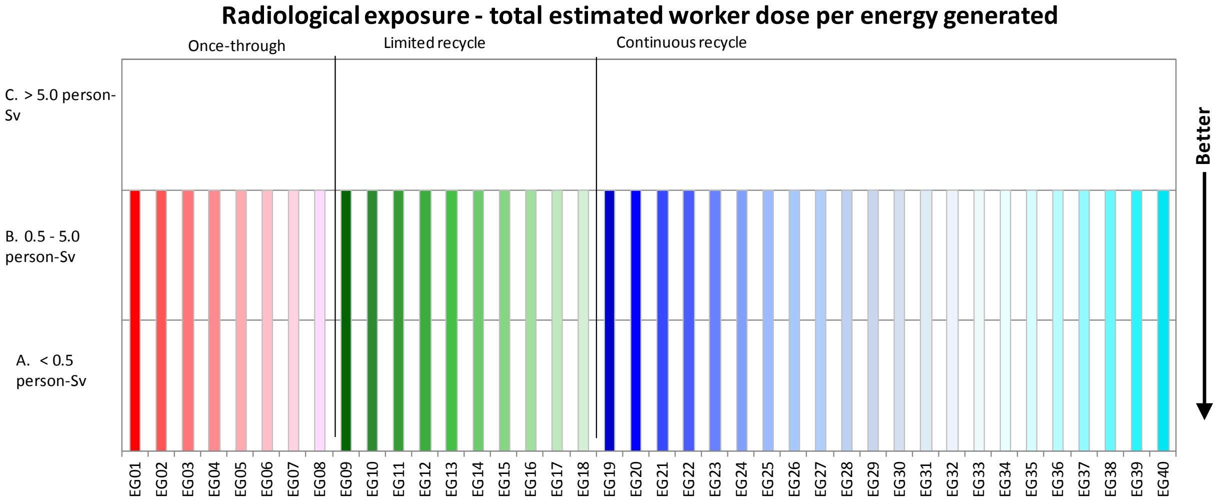


Figure D-2.13-3. Metric Data for Occupational Radiation Exposure for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups

Table D-2.13-1 provides the Metric Data for all of the Evaluation Groups. If the improvements represented by bin “A” were considered significant then the promising Evaluation Groups would be found within this bin. However there were no Evaluation Groups that appear to have the potential to provide improvement in the worker dose required over the Basis of Comparison.

Supporting R&D, and Insights

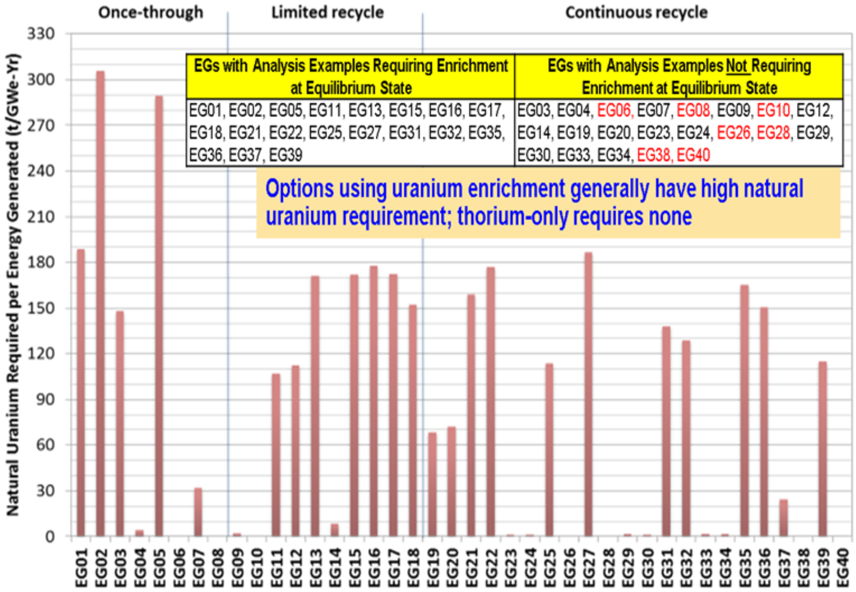
Since there were no Evaluation Groups identified that appeared to have the potential to provide improvement in the radiological exposure required with respect to the Basis of Comparison, no specific recommendations on R&D activities are made other than the potential radiological exposure should be considered as implementing technologies are selected and facilities are designed.

D-2.14 Natural Uranium Required per Energy Generated

Calculation of Metric Information

The natural uranium required per energy generated is defined as the natural uranium fuel resources required for a particular fuel cycle option. The information for this metric is obtained directly from the "Mass Flow Data" table for each Analysis Example (see information in Appendix B-5). Since the information in the tables of Appendix B-5 is for 100 GWe-yr capacity, these data are divided by 100 to obtain the value per GWe-yr. Additionally, the data have been normalized to ensure a consistent thermal efficiency of the power generation unit of 33%, which is the common basis used for the Evaluation and Screening. The mass normalization factors used for the 40 Analysis Examples are provided in Table D-1.1.

The data for the Analysis Examples for the 40 Evaluation Groups are provided in Figure D-2.14.1. The required natural uranium resource varies from 0 to 306 t/GWe-yr (some fuel cycles do not use uranium, i.e., thorium only fuel cycles). The fuel cycle options that require enriched uranium fuel have higher values for the natural uranium required metric compared to fuel cycle options that do not need enriched uranium fuel.



EGs with Analysis Examples Requiring Enrichment at Equilibrium State	**EGs with Analysis Examples Not Requiring Enrichment at Equilibrium State**
EG01, EG02, EG05, EG11, EG13, EG15, EG16, EG17, EG18, EG21, EG22, EG25, EG27, EG31, EG32, EG35, EG36, EG37, EG39	EG03, EG04, EG06, EG07, EG08, EG09, EG10, EG12, EG14, EG19, EG20, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG38, EG40

Options using uranium enrichment generally have high natural uranium requirement; thorium-only requires none

Figure D-2.14.1. Calculated Natural Uranium Required per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

For options requiring uranium enrichment, typically the higher the enrichment, the higher the uranium resource required unless the fuel cycle included consumption of the recovered uranium from used fuel reprocessing. The Analysis Example for EG02 requires the highest mass of uranium resource because the feed material is only enriched uranium with higher enrichment. The thorium-only Analysis Examples have no uranium resource requirements (see results for EG06, EG08, EG10, EG26, EG28, EG38, and EG40, which have Analysis Examples using thorium-only fuel).

Development of Metric Data

The 40 Analysis Examples provide an initial indication of the performance of the Evaluation Groups. Since there are many possible fuel cycle options in an Evaluation Group, it was realized that the metric information calculated for the Evaluation Group would show some variability. Consequently, it was determined that binning the metric information derived from the 40 Analysis Examples would better inform on the potential of the Evaluation Groups. In the following, the calculated metric information for natural uranium required, the approach for binning, and for re-binning some evaluations groups are discussed.

The calculated natural uranium required per energy generated is displayed in Figure D-2.14.2, along with the bin boundaries. On Figure D-2.14.2, the calculated information has been ordered from the lowest performing (highest mass) Evaluation Group to the highest performing (lowest mass) and does not reflect the re-binning of a few evaluations groups as discussed below.

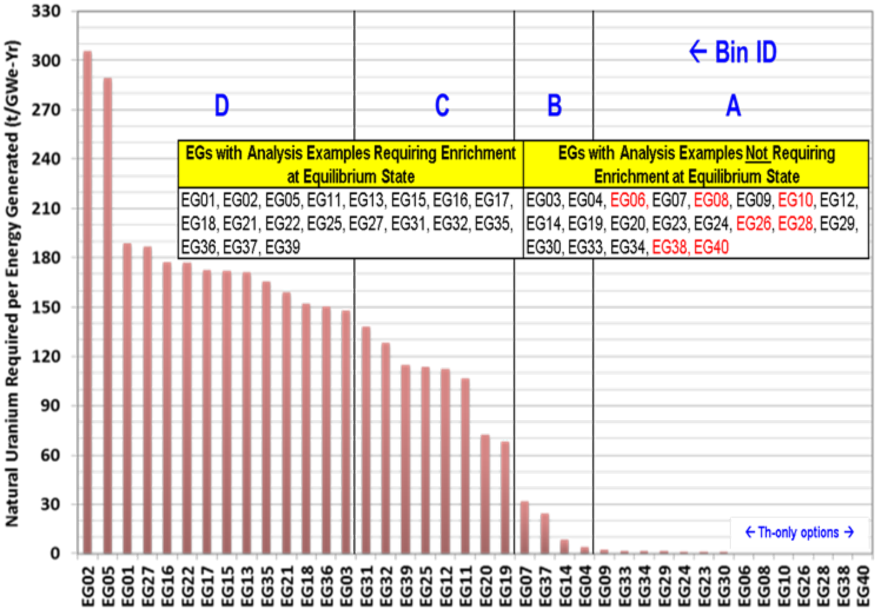


Figure D-2.14.2. Calculated Natural Uranium Required per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Decreasing Mass.

The metric bins were defined to recognize the variability in the Natural Uranium Required per Energy Generated across the different fuel cycle options included in an Evaluation Group, and in consideration of the following factors:

- The calculated natural uranium required varies by two orders of magnitude over the 40 Analysis Examples for the Evaluation Groups.
- Bins should recognize fuel cycles and the magnitude of change of the metric over possible fuel cycle options in percent uranium utilized (value of which range from zero to about <100%).
- Include a group that represents the uranium utilization (in percent) that is typically obtained by currently operating nuclear fuel cycles using LWRs, CANDU, and Advanced Gas Cooled reactors (in the U.K. for example).

With this information, the bins that were determined for the natural uranium required metric, ranging from A (the highest performance bin) to D (the lowest performance bin), are presented in Table D-2.14.1.

Table D-2.14.1. Metric Bins for Natural Uranium Required per Energy Generated.

Bin ID	Data Range (t/GWe-yr)	Bin Description
A	< 3.8	Natural uranium mass required < 3.8 t/GWe-yr; includes fuel cycle options with uranium utilization ≥ 30% and thorium-only options
B	3.8 to < 35.0	Natural uranium mass required from 3.8 t/GWe-yr to < 35.0 t/GWe-yr; includes options with uranium utilization ≥ 3% and < 30%; bounded by performance of advanced approaches constrained by physics performance without fuel reprocessing
C	35.0 to < 145.0	Natural uranium mass required from 35.0 t/GWe-yr to < 145.0 t/GWe-yr; includes options with uranium utilization ≥ 0.8% and < 3%; bounded by performance of more traditional proposals for increasing utilization
D	≥ 145.0	Natural uranium required mass equals or greater than 145.0 t/GWe-yr; contains options with uranium utilization similar to or lower than those of currently operating thermal reactors (LWRs and CANDU); contains the Basis of Comparison

The bins obtained for the Evaluation Groups based on this approach are listed in Table D-2.14.2 (third column). For a few Evaluation Groups, the calculated Natural Uranium Required per Energy Generated for the Analysis Example was not considered representative of the overall performance of that Evaluation Group, and a decision was made to reassign those Evaluation Groups to different bins. The fourth and fifth columns of Table D-2.14.2 are the final Metric Data and the explanations for any changes from the initial binning. The Evaluation Group EG07 was re-binned based on the realization that it would have given similar metric data result as EG08 if an FFH instead of ADS and similar modeling assumptions had been used as the Analysis Example and hence it is now in the same bin as EG08 (because of the high burnup in EG08, fuel utilization is about 75%).

Table D-2.14.2. Metric Data for Natural Uranium Required for the Evaluation Groups.

EG	Calculated Mass (t/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG01	188.63	D	D	
EG02	305.73	D	D	
EG03	147.87	D	D	
EG04	4.00	B	B	
EG05	289.20	D	D	
EG06	0.00	A	A	
EG07	32.03	B	A	EG07 would have given similar metric data result as EG08 if an FFH instead of ADS and similar modeling assumptions had been used in its Analysis Example.
EG08	0.00	A	A	
EG09	2.25	A	A	

EG	Calculated Mass (t/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG10	0.00	A	A	
EG11	106.80	C	C	
EG12	112.46	C	C	
EG13	171.16	D	D	
EG14	8.38	B	B	
EG15	171.96	D	D	
EG16	177.56	D	D	
EG17	172.41	D	D	
EG18	152.16	D	D	
EG19	68.41	C	C	
EG20	72.26	C	C	
EG21	159.02	D	D	
EG22	176.86	D	D	
EG23	1.34	A	A	
EG24	1.37	A	A	
EG25	113.54	C	C	
EG26	0.00	A	A	
EG27	186.62	D	D	
EG28	0.00	A	A	
EG29	1.49	A	A	
EG30	1.33	A	A	
EG31	137.96	C	C	
EG32	128.50	C	C	
EG33	1.64	A	A	
EG34	1.55	A	A	
EG35	165.37	D	D	
EG36	150.54	D	D	
EG37	24.36	B	B	
EG38	0.00	A	A	
EG39	114.85	C	C	
EG40	0.00	A	A	

*The light blue background is used to denote Evaluation Groups with Analysis Examples using Th/U fuel; the light purple background denotes Evaluation Groups with Th-only fuel, and the white background denotes Evaluation Groups with U-only fuel.

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.14.3 (note that the same data is provided in the fourth column of Table D-2.14.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

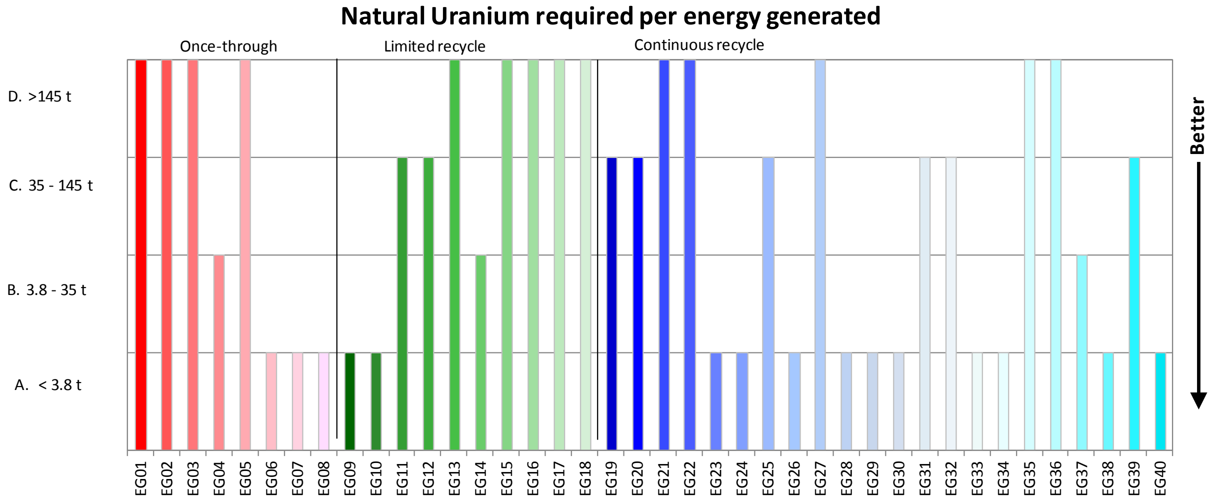


Figure D-2.14.3. Metric Data for the Mass of Natural Uranium Required per Energy Generated for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups for Reducing Natural Uranium Required per Energy Generated

The Evaluation Group EG01, the Basis of Comparison, is in bin D because its Analysis Example has a Natural Uranium Required mass of ~189 t/GWe-yr. If the level of improvement represented by bin A was considered significant, then the corresponding set of Evaluation Groups meeting or exceeding that level of improvement is listed as promising. Those Evaluation Groups include:

Bin A < 3.8 t/GWe-yr	EG06, EG07, EG08, EG09, EG10, EG23, EG24, EG26, EG28, EG29, EG30, EG33, EG34, EG38, EG40

This bin provides much more than a factor of 10 reduction in the Natural Uranium Required per Energy Generated relative to bin D.

These Evaluation Groups are mostly those with continuous recycle options, a few with higher burnup of fuel with or without enrichment support, or thorium-only options. Of these Evaluation Groups, the set of EG06, EG08, EG10, EG26, EG28, EG38, and EG40, had Analysis Examples that only used thorium. EG09 and EG10 are limited recycle Evaluation Groups. The Analysis examples for EG23, EG24, EG29, EG30, EG33, and EG34 are continuous recycle cases using uranium fuels only.

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

Bin B 3.8 to < 35.0 t/GWe-yr	EG04, EG14, EG37

The Analysis Example for EG04 is a fast-spectrum system in which only depleted or natural uranium is used as input fuel feed material in the equilibrium state. All the evaluations groups in bins A and B 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%).

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

Bin C 35.0 to < 145.0t/GWe-yr	EG11, EG12, EG19, EG20, EG25, EG31, EG32, EG39

EG11 and EG12 are limited recycle fuel cycles. The EG11 Analysis Example is a thorium fuel dominant option, but also requires enriched uranium fuel because the bred U-233 is insufficient to maintain criticality. The Analysis Examples for EG12, EG19, and EG20 do not require enriched uranium fuels, but use a significant amount of natural uranium to supply the fissile U-235 for the heavy water reactors contained in the associated fuel cycle options. The Analysis Examples for EG25, EG31, EG32, and EG35 are continuous recycle options that require enrichment.

Supporting R&D and Insights

Based on the identified Evaluation Groups above, arising from the conditional statements on promising options, following are the R&D activities that would support the development of fuel cycles that require lower amount of uranium resources than the basis of comparison:

- 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.

D-2.15 Natural Thorium Required per Energy Generated

Calculation of Metric Information

The natural thorium required per energy generated is defined as the natural thorium fuel resources required for a particular fuel cycle option. The natural thorium required per energy generated is obtained directly from the “Mass Flow Data” table for each Analysis Example (see information in Appendix B-5). Since the information in the tables of Appendix B-5 are provided for 100 GWe-yr capacity, these data are divided by 100 to obtain the value per GWe-yr. Additionally, the mass flow data have been normalized to ensure a consistent thermal efficiency of the power generation unit of 33%, which is the common basis used for the Evaluation and Screening. The mass normalization factors used for the 40 Analysis Examples are provided in Table D-1.1.

The data for the Analysis Examples for the 40 Evaluation Groups are provided in Figure D-2.15.1. The required natural thorium resource varies from 0 to 11 t/GWe-yr.

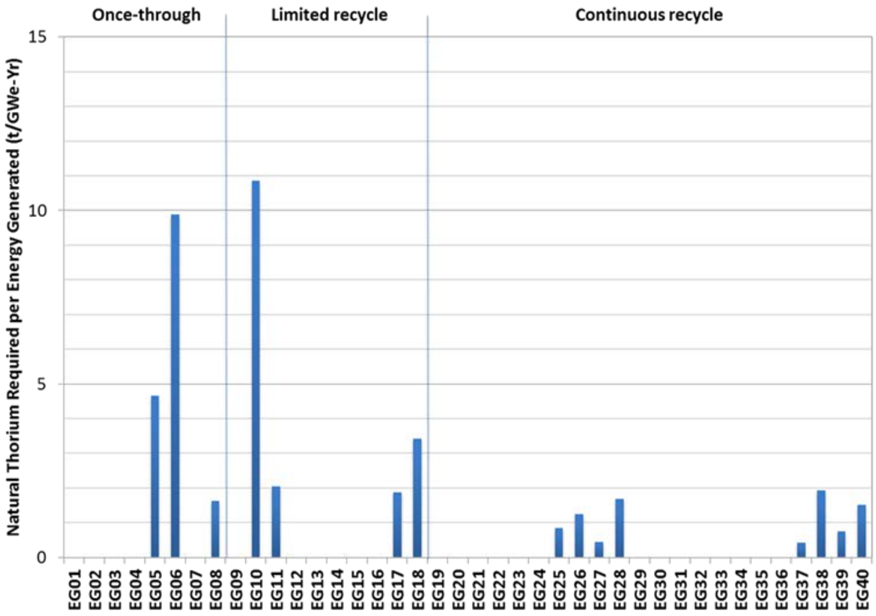


Figure D-2.15.1. Calculated Natural Thorium Required per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Evaluation Group Number.

Since thorium does not have fissile isotope, fissile material is required in some thorium fuel cycle options to maintain criticality. The fissile material could be the bred fissile (U-233) or enriched uranium. External neutron sources instead of neutrons from fission could also be used to sustain the energy generation process. Enriched uranium is the fissile source for options with thorium and uranium fuel (EG05, EG11, EG17, EG18, EG25, EG27, EG37, and EG39), while it is the neutron sources from externally-driven systems for the Analysis Examples of EG06, EG08, and EG40, it is bred U-233 from continuous on-line reprocessing for the Analysis Examples of EG10 and EG26, and it is the bred fissile material from fast reactor for the Analysis Examples of EG28 and EG39.

Comparison of information in Figure D-2.15.1 to that in D-2.14.1 might give the impression that thorium gives more energy than uranium per given mass, because of the nature of the data presented. This interpretation would be incorrect because the thorium cases are either thorium only options using the breed and burn concept, or continuous recycle cases, or are being supported by uranium (specifically enriched uranium). Figure D-2.15.2 shows the natural uranium or thorium masses required for the continuous recycle fuel cycle options without uranium enrichment. The Analysis Example for EG26, EG28, EG38 and EG40 use thorium fuels, while those for EG23, EG24, EG29, EG30, EG33 and EG34 use uranium fuels. This figure confirms what is expected from physics reasoning that the masses should be about the same, since the fission of ~1 gm of heavy metal produces about 1 MW-day of energy. Differences are due to the different effective thermal efficiencies and energy yield from fission.

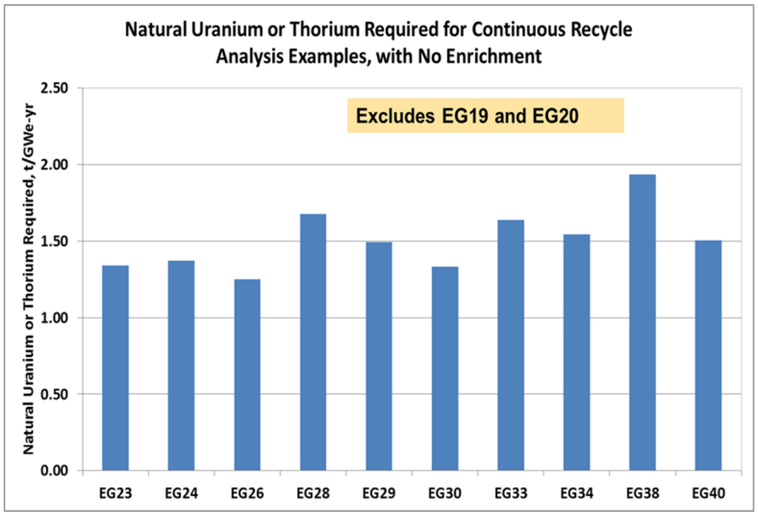


Figure D-2.15.2. Comparison of Natural Uranium and Thorium Required for Fuel Cycle Options Not Using Uranium Enrichment.

Development of Metric Data

The 40 Analysis Examples provide an initial indication of the performance of the Evaluation Groups. Since there are many possible options within an Evaluation Group, it was realized that the metric information calculated for the Evaluation Group could show some variability. Consequently, it was considered better informing on the Evaluation Groups by binning the metric information derived from the 40 Analysis Examples. So, in what follows, the natural thorium required metric information calculated, the approach for binning, and for re-binning some evaluations groups are discussed.

The calculated natural thorium required per energy generated is displayed in Figure D-2.15.3 along with the bin boundaries. On Figure D-2.15.3, the calculated information has been ordered from the lowest performing (highest mass) to the highest performing (lowest mass) and does not reflect the re-binning of a few evaluations groups as discussed below. "T" on Figure D-2.15-3 indicates the option with thorium fuel only, while other options have thorium and uranium fuel.

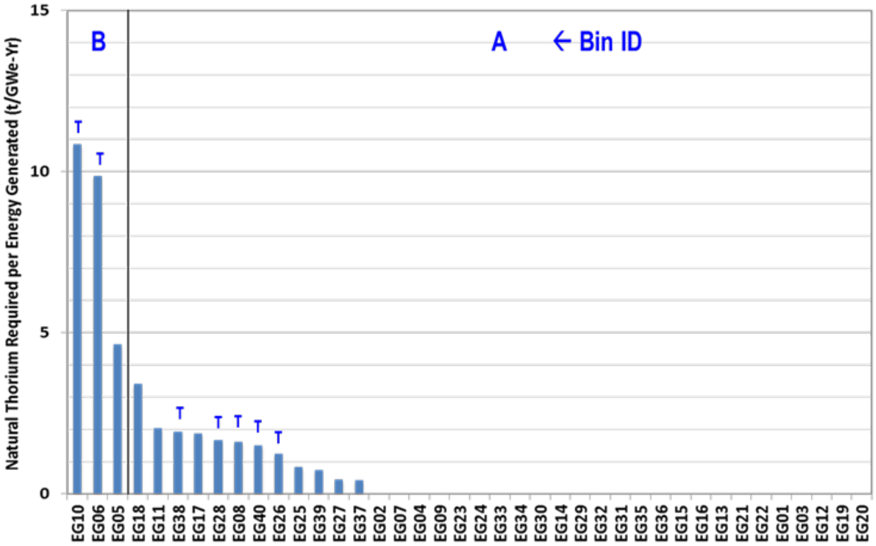


Figure D-2.15.3. Calculated Natural Thorium Required per Energy Generated for the Analysis Examples of the 40 Evaluation Groups Ordered by Decreasing Mass.

The metric bins were defined to recognize the variability in the Natural Thorium Required per Energy Generated across the different fuel cycle options included in an Evaluation Group, and in consideration of the following factors:

- The calculated *natural thorium required* varies by factor of 25 over the 40 Analysis Examples for the Evaluation Groups.
- Bins should recognize fuel cycles and the magnitude of change of the metric over possible fuel cycle options in percent thorium utilized (value would be zero to about <100%).
- Use a bin structure consistent with that of uranium to ensure a reasonable combination of the metrics.
- The performance of fuel cycles within the Evaluation Group will vary, but the differences in the calculated values between fuel cycles within an Evaluation Group are not material to informing on the overall performance of that group relative to the basis of comparison.

With this information, the bins that were determined for the natural thorium required metric, ranging from A (the highest performance bin) to D (the lowest performance bin), are presented in Table D-2.15.1.

Table D-2.15.1. Metric Bins for Natural Thorium Required per Energy Generated.

Bin ID	Data Range (t/GWe-yr)	Bin Description
A	< 3.8	Natural thorium mass required < 3.8 t/GWe-yr; includes fuel cycle options with thorium utilization ≥ 30% or uranium-only options; Contains Basis of Comparison
B	3.8 to < 35.0	Natural thorium mass required from 3.8 t/GWe-yr to < 35.0 t/GWe-yr; includes options with thorium utilization ≥ 3% and < 30%
C	35.0 to < 145.0	Natural thorium mass required from 35.0 t/GWe-yr to < 145.0 t/GWe-yr; includes options with thorium utilization ≥ 0.8% and < 3%
D	≥ 145.0	Natural thorium mass required equals or greater than 145.0 t/GWe-yr.

The bins obtained for the Evaluation Groups based on this approach are provided in Table D-2.15.2 (third column). For a few Evaluation Groups, the calculated Natural Thorium Required per Energy Generated for the Analysis Example was not considered representative of the overall performance of that Evaluation Group, and a decision was made to reassign those Evaluation Groups to different bins. The fourth and fifth columns of Table D-2.15.2 are the final metric data and explanations for changes from the initial binning. The Evaluation Group EG06 was re-binned based on the realization that it would have given similar metric data result as EG08 if similar modeling assumptions had been used in its Analysis Example and hence it is now in the same bin as EG08.

Table D-2.15.2. Metric Data for Natural Thorium Utilization for the Evaluation Groups.

EG	Calculated Mass (t/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG01	0.00	A	A	
EG02	0.00	A	A	
EG03	0.00	A	A	
EG04	0.00	A	A	

EG	Calculated Mass (t/GWe-yr)	Analysis Example Bin Data	Metric Data	Reasons for Changing Analysis Example Bin Data
EG05	4.65	B	B	
EG06	9.88	B	A	EG06 would have given similar metric data result as EG08 if similar modeling assumptions had been used in its Analysis Example.
EG07	0.00	A	A	
EG08	1.62	A	A	
EG09	0.00	A	A	
EG10	10.86	B	B	
EG11	2.05	A	A	
EG12	0.00	A	A	
EG13	0.00	A	A	
EG14	0.00	A	A	
EG15	0.00	A	A	
EG16	0.00	A	A	
EG17	1.88	A	A	
EG18	3.42	A	A	
EG19	0.00	A	A	
EG20	0.00	A	A	
EG21	0.00	A	A	
EG22	0.00	A	A	
EG23	0.00	A	A	
EG24	0.00	A	A	
EG25	0.85	A	A	
EG26	1.25	A	A	
EG27	0.45	A	A	
EG28	1.68	A	A	
EG29	0.00	A	A	
EG30	0.00	A	A	
EG31	0.00	A	A	
EG32	0.00	A	A	
EG33	0.00	A	A	
EG34	0.00	A	A	
EG35	0.00	A	A	
EG36	0.00	A	A	
EG37	0.43	A	A	
EG38	1.93	A	A	
EG39	0.75	A	A	
EG40	1.51	A	A	

*The light blue background is used to denote Evaluation Groups with Analysis Examples using Th/U fuel; the light purple background denotes Evaluation Groups with Th-only fuel, and the white background denotes Evaluation Groups with U-only fuel.

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.15.4 (note that the same data is provided in the fourth column of Table D-2.15.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

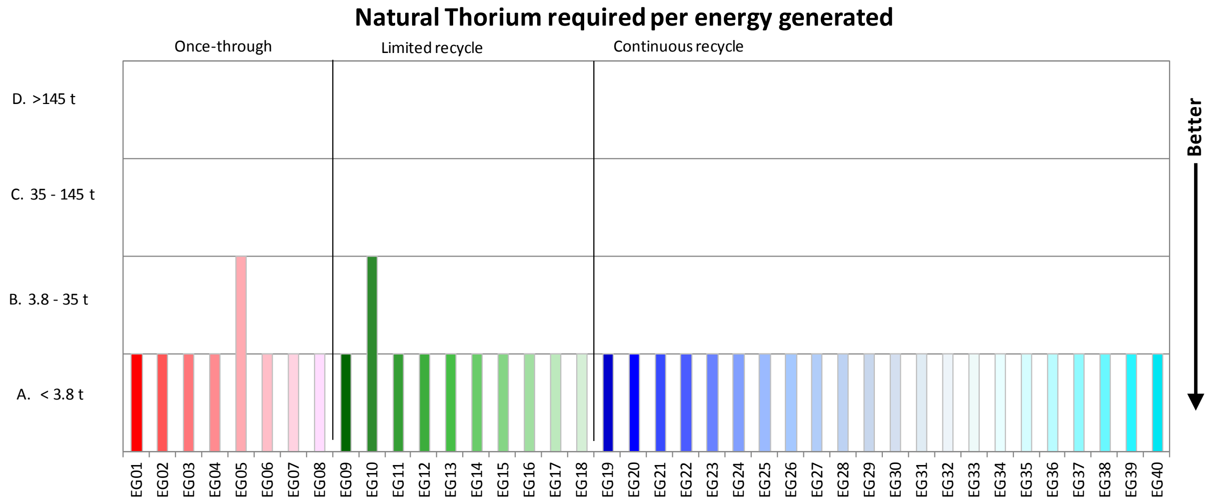


Figure D-2.15.4. Metric Data for Mass of Natural Thorium Required per Energy Generated for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Promising Groups for Reducing Natural Thorium Required per Energy Generated

The Evaluation Group EG01, the Basis of Comparison, is in bin A because this is a group that does not use thorium fuel. Thus there are no Evaluation Groups that are better performing from the viewpoint of the natural thorium required metric. All the Evaluation Groups are in bin A with the exception of EG05 and EG10.

Supporting R&D and Insights

Since nearly all the Evaluation Groups performed similarly for this metric, what follows is a listing of the R&D that would be required to implement various options using thorium feed in the U.S.:

- Thorium mining, milling, and fuel processing and preparation technologies to implement options using thorium.
- Separation technologies for the limited and continuous recycle options
- 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

To achieve low natural thorium requirement without uranium enrichment support and no recycling the following additional R&D would be required.

- 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
- 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.

D-2.16 Development Cost

Approach for determining metric data

The approach for determining the development cost metric data for each Evaluation Group uses an approach based on summing the development cost data for the fuel cycle processes that compose the evaluation group. In Appendix C-7, fuel cycle process data for the Development Cost is provided for each fuel cycle process and using the fuel cycle process to Evaluation Group mapping table in Appendix C-4, the fuel cycle process data can be combined to obtain the overall Metric Data for the Evaluation Group. Since the fuel cycle process data is binned, the combination approach uses the bin mid-point to represent the bin value to allow a summation for the Evaluation Group. The summed cost for the Evaluation Group is then assigned to the appropriate development cost bin.

Metric data

The bin descriptions for the development cost bins in this table are defined in Appendix C-7 and are repeated in Table D-2.16.1 for reference when considering the Metric Data.

Table D-2.16.1. Development Cost Bin Descriptions.

Bin	Bin Descriptions for Development Cost
Bin A: No Development Needed (Already at TRL6 or beyond)	No R&D needed. Technology is already at TRL 6 or beyond. Development cost is $0. This bin contains the Basis of Comparison.
Bin B: Development costs of < $200M	R&D required but is limited in scope and can be supported with existing facilities with little or no modifications. Development costs expected to be less than $200 million
Bin C: Development cost of $200M- $2B	R&D required, but can primarily be performed without significant investment in new major nuclear facilities for engineering/pilot scale demonstration. May, for example, just require modification of existing facilities. Development costs expected to be between $200 million and $2 billion.
Bin D: Development cost of $2B - $10B	R&D required including construction of a major nuclear facility to provide an engineering/pilot scale demonstration of one component of a fuel cycle. Development costs expected to be between $2 billion and $10 billion.
Bin E: Development cost of $10B - $25B	Significant R&D required including construction of several nuclear facilities to provide an engineering/pilot scale demonstration of several components of a fuel cycle. Alternatively, the scale of the facilities required for engineering/pilot scale demonstration is large and results in significantly increased cost. Development costs expected to be between $10 billion and $25 billion.
Bin F: Development cost of >$25B	Very significant R&D required including construction of many new facilities to provide an engineering/pilot scale demonstration of several components of the fuel cycle. May require more than one scale of facility development for particular fuel cycle components. Development cost expected to be greater than $25 billion.

The development cost Metric Data for each Evaluation Group is provided in Table D-2.16.2 and is presented on Figure D-2.16.1.

Table D-2.16.2. Development Cost Metric Data for the 40 Evaluation Groups.

Evaluation Group	Metric Data
EG01	Bin A
EG02	Bin B
EG03	Bin A
EG04	Bin D
EG05	Bin B
EG06	Bin E
EG07	Bin E
EG08	Bin E
EG09	Bin E
EG10	Bin E
EG11	Bin E
EG12	Bin C
EG13	Bin C
EG14	Bin D
EG15	Bin D
EG16	Bin E
EG17	Bin D
EG18	Bin E
EG19	Bin C
EG20	Bin E
EG21	Bin C
EG22	Bin E
EG23	Bin D
EG24	Bin E
EG25	Bin E
EG26	Bin E
EG27	Bin E
EG28	Bin E
EG29	Bin D
EG30	Bin E
EG31	Bin D
EG32	Bin E
EG33	Bin E
EG34	Bin F
EG35	Bin E
EG36	Bin F
EG37	Bin E
EG38	Bin E
EG39	Bin F
EG40	Bin F

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.16.1 (note that the same data is provided in the second column of Table D-2.16.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

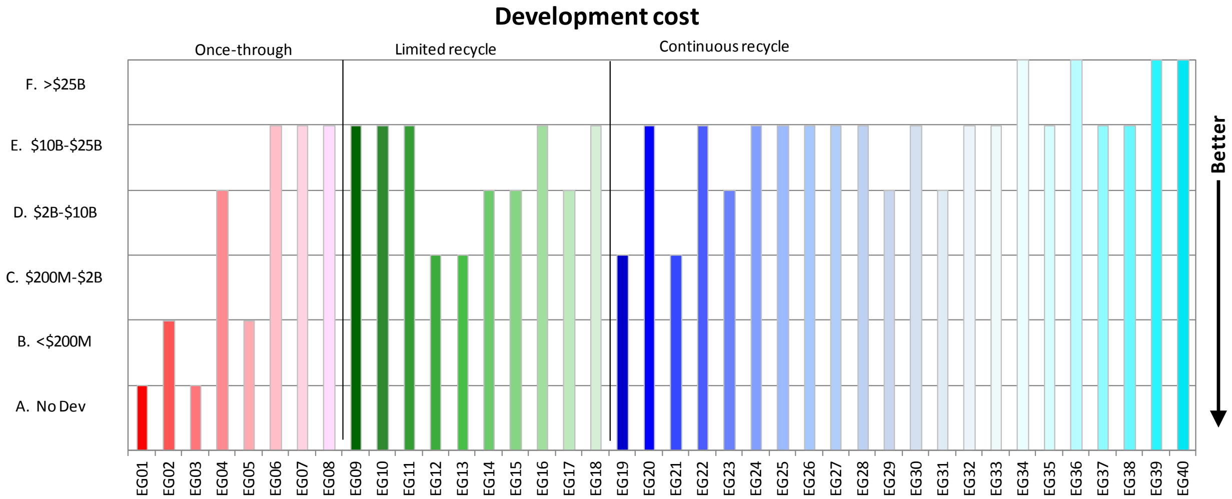


Figure D-2.16.1. Metric Data for Development Cost for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Metric Observations

The development cost metric is a metric for one of the "challenge" criteria as described in Appendix A, for which the Basis of Comparison has the lowest level of “challenge.” As a consequence, this is a metric for which there are no promising Evaluation Groups. All fuel cycle options with the exception of the currently deployed Basis of Comparison EG01 and EG03 all require some development cost and by definition are in lower performing bins. However, based on a ranking of the Evaluation Groups by bin, observations of the Evaluation Groups based on the Development cost metric data are as follows:

- Fuel cycles that are already deployed have the highest overall ranking (no development cost). This includes EG01 and EG03. These EGs are included in Bin A.
- Highly ranked fuel cycle Evaluation Groups include fuel cycles that require only fuels development including once-through fuel cycles that can use existing thermal reactors with uranium fuels that can achieve higher burnups, EG02, and thorium fuels, EG05. These fuel cycles require only the necessary research to quality the fuel, which can be largely performed with existing research facilities. These EGs are included in Bin B.
- Fuel cycles with the largest development costs are those that require the introduction of multiple technologies including reactor types that are not currently deployed (advanced thermal reactors, fast reactors, and EDS), reprocessing, and recycle of TRU and U-233 containing fuels. These EGs populate the remaining Bins C-F, with development cost Bins C representing use of existing types of reactors, and D representing introduction of a single type of new reactor types and development cost Bins E and F representing multiple new reactor types and associated facilities.

D-2.17 Development Time

Approach for determining metric data

The approach for determining the development time metric data for each Evaluation Group uses an approach based on using the longest development time of all fuel cycle processes that compose the evaluation group. In Appendix C-7, fuel cycle process data for the Development Cost is provided for each fuel cycle process and using the fuel cycle process to Evaluation Group mapping table in Appendix C-4, the fuel cycle process data can be combined to obtain the overall metric data for the Evaluation

Group. Since the fuel cycle process data is binned, the fuel cycle process with the bin representing the longest development time bin is selected as the metric data for the Evaluation Group.

Metric data

The descriptions for the development cost bins are defined in Appendix C and are repeated in Table D-2.17.1.

Table D-2.17.1. Development Time Bin Descriptions.

Bin	Bin Descriptions for Development Time
Bin A: No Development Needed (Already at TRL6 or beyond)	No R&D needed. Technology is already at TRL 6 or beyond. Development time is 0 years. This bin contains the Basis of Comparison.
Bin B: < 5 Years of development needed	R&D required, but most of the required capabilities already demonstrated and any additional R&D is limited in scope and can be supported with existing facilities with little or no modifications. Estimated development time is less than 5 years.
Bin C: 5 – 10 years of development needed	R&D required, but many of the required capabilities are either already demonstrated or nearly demonstrated. Additional engineering/pilot scale in the near term likely using existing facilities or based on historical experience. Example may be the qualification of a well-established fuel. Estimated development time is 5-10 years.
Bin D: 10 – 25 years of development needed	R&D required that requires extended development time to arrive at a workable capability and demonstration at the engineering/pilot scale. Estimated development time is 10-25 years.
Bin E: 25 – 50 years of development needed	Significant R&D required that may require more fundamental development at laboratory scale before developing capabilities that can be demonstrated at engineering/pilot scale. Estimated development time is 25-50 years.
Bin F: > 50 years of development needed	Very significant R&D required that may require significant technical breakthroughs, new discoveries or extended research, development of long-lead time laboratory experiments before engineering/pilot demonstration. Estimated development time is greater than 50 years.

The development time metric data for each Evaluation Group is provided in Table D-2.17.2.

Table D-2.17.2. Development Time Metric Data for the 40 Evaluation Groups.

Evaluation Group	Metric Data
EG01	Bin A
EG02	Bin B
EG03	Bin A
EG04	Bin D
EG05	Bin B
EG06	Bin D
EG07	Bin D
EG08	Bin D
EG09	Bin D
EG10	Bin D
EG11	Bin D
EG12	Bin C
EG13	Bin C

EG14	Bin D
EG15	Bin D
EG16	Bin D
EG17	Bin D
EG18	Bin D
EG19	Bin C
EG20	Bin D
EG21	Bin C
EG22	Bin D
EG23	Bin D
EG24	Bin D
EG25	Bin D
EG26	Bin D
EG27	Bin D
EG28	Bin D
EG29	Bin D
EG30	Bin D
EG31	Bin D
EG32	Bin D
EG33	Bin D
EG34	Bin D
EG35	Bin D
EG36	Bin D
EG37	Bin D
EG38	Bin D
EG39	Bin D
EG40	Bin D

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.17.1 (note that the same data is provided in the second column of Table D-2.17.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

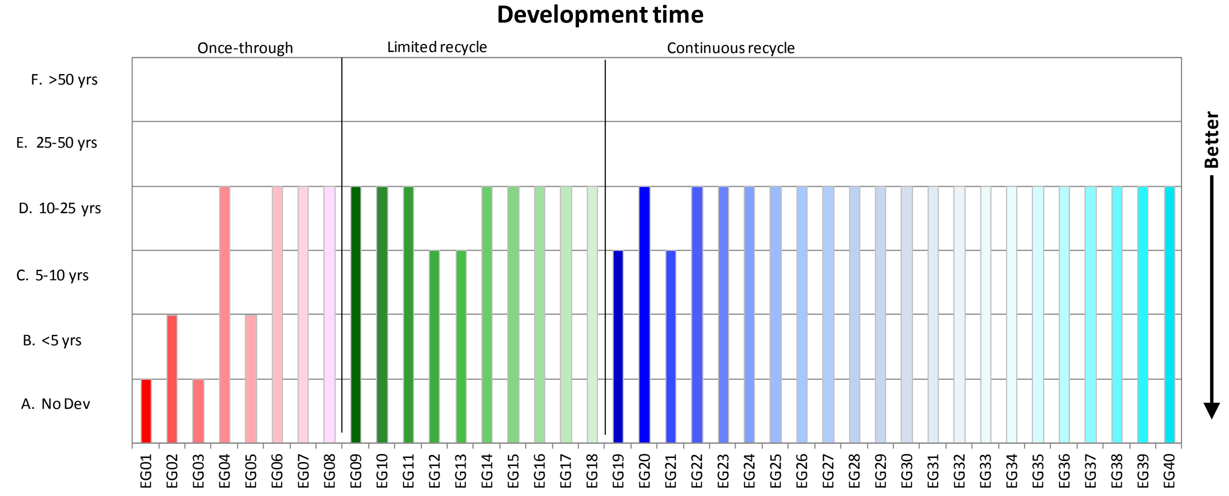


Figure D-2.17.1. Metric Data for Development Time for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Metric Observations

The development time metric is a metric for one of the "challenge" criteria as described in Appendix A, for which the Basis of Comparison has the lowest level of "challenge." As a consequence, this is a metric for which there are no promising Evaluation Groups. All fuel cycle options with the exception of the currently deployed Basis of Comparison EG01 and EG03 all require some development time and by definition are in lower performing bins. However, based on a ranking of the Evaluation Groups by bin, observations of the Evaluation Groups based on the development time metric data are as follows:

- Development time is correlated with development cost with those systems that take longer to develop generally having higher development costs.
- Fuel cycles that are already deployed have the best performance (no development time). This includes EG01 and EG03 Evaluation Groups. These correspond to Bin A.
- Fuel cycles that require only fuel qualification have <5 year development time and are represented by Bin B. This includes EG03 and EG05.
- Fuel cycles that require only fuels development or use Pu-only recycle in existing thermal reactor types have a 5-10 year development time (Bin C) and include EG12, EG13, EG19, and EG21.
- All other fuel cycles that include the use of reactor types that are currently not deployed (advanced thermal reactors, fast reactors, and EDS), recycle of TRU and/or U-233 containing fuels have development times that range of 10-25 years (Bin D).
- No fuel cycles were identified that would require more than 25 year development time.

D-2.18 Deployment Cost from Prototypic Validation to FOAK Commercial

Approach for determining metric data

The approach for determining the deployment cost metric data for each Evaluation Group uses an approach based on summing the deployment cost data for the fuel cycle processes that the evaluation group is composed. In Appendix C-7, fuel cycle process data for the Deployment Cost from Prototypic Validation for first-of-a-kind (FOAK) Commercial is provided for each fuel cycle process and using the fuel cycle process to Evaluation Group mapping table in Appendix C-4, the fuel cycle process data can be combined to obtain the overall metric data for the Evaluation Group. Since the fuel cycle process data is binned, the combination approach uses the bin mid-point to represent the bin value to allow a summation for the Evaluation Group. The summed cost for the Evaluation Group is then assigned to the appropriate development cost bin.

Metric data

The bin descriptions for the development cost bins in this table are defined in Appendix C and are repeated in Table D-2.18.1.

Table D-2.18.1. Deployment Cost Bin Descriptions.

Bin ID	**Bin Descriptions for Deployment Cost**
Bin A: Previously deployed as FOAK or beyond	Technology already has a FOAK (or beyond) commercial deployment. FOAK deployment cost is $0. This bin contains the Basis of Comparison.
Bin B: < $2B to deploy FOAK	Deployment of a FOAK commercial system may, for example, require small-scale nuclear facility or modifications to existing nuclear facility. Estimated cost to go from an engineering/pilot scale system to FOAK is less than $2 billion
Bin C: $2B - $10B to deploy FOAK	Deployment of a FOAK commercial system represents a single nuclear facility or a few small-scale nuclear facilities. Estimated costs to go from an engineering/pilot scale system to FOAK is between $2 billion and $10 billion
Bin D: $10B - $25B to deploy FOAK	Deployment of a FOAK commercial system represents a single large-scale nuclear facility or several medium-scale nuclear facilities. Estimated cost to go from an engineering/pilot scale system to FOAK is between $10 billion and $25 billion
Bin E: $25B - $50B to deploy FOAK	Deployment of a FOAK commercial system represents a significant effort to move from engineering/pilot scale to first-of-a-kind commercial system (FOAK) that may include several large-scale nuclear facilities. Estimated cost to go from an engineering/pilot scale system to FOAK is between $25 billion and $50 billion
Bin F: >$50B to deploy FOAK	Deployment of a FOAK commercial system represents a very significant effort to move from engineering/pilot scale to FOAK system that may include several large-scale nuclear facilities that require several stages of deployment representing additional scales of facilities needed to achieve FOAK. Estimated cost to go from an engineering/pilot scale system to FOAK is over $50 billion

The deployment cost metric data for each Evaluation Group is provided in Table D-2.18.2.

Table D-2.18.2. Metric Data for Deployment Cost from Prototypic Validation to FOAK Commercial for the 40 Evaluation Groups.

Evaluation Group	**Metric Data**
EG01	Bin A
EG02	Bin B
EG03	Bin A
EG04	Bin C
EG05	Bin B
EG06	Bin D
EG07	Bin D
EG08	Bin D
EG09	Bin E
EG10	Bin E
EG11	Bin E
EG12	Bin D
EG13	Bin D
EG14	Bin E
EG15	Bin D
EG16	Bin E

EG17	Bin E
EG18	Bin E
EG19	Bin D
EG20	Bin E
EG21	Bin D
EG22	Bin E
EG23	Bin D
EG24	Bin E
EG25	Bin E
EG26	Bin E
EG27	Bin E
EG28	Bin E
EG29	Bin E
EG30	Bin E
EG31	Bin D
EG32	Bin E
EG33	Bin E
EG34	Bin E
EG35	Bin E
EG36	Bin E
EG37	Bin E
EG38	Bin E
EG39	Bin E
EG40	Bin E

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.18.1 (note that the same data is provided in the second column of Table D-2.18.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

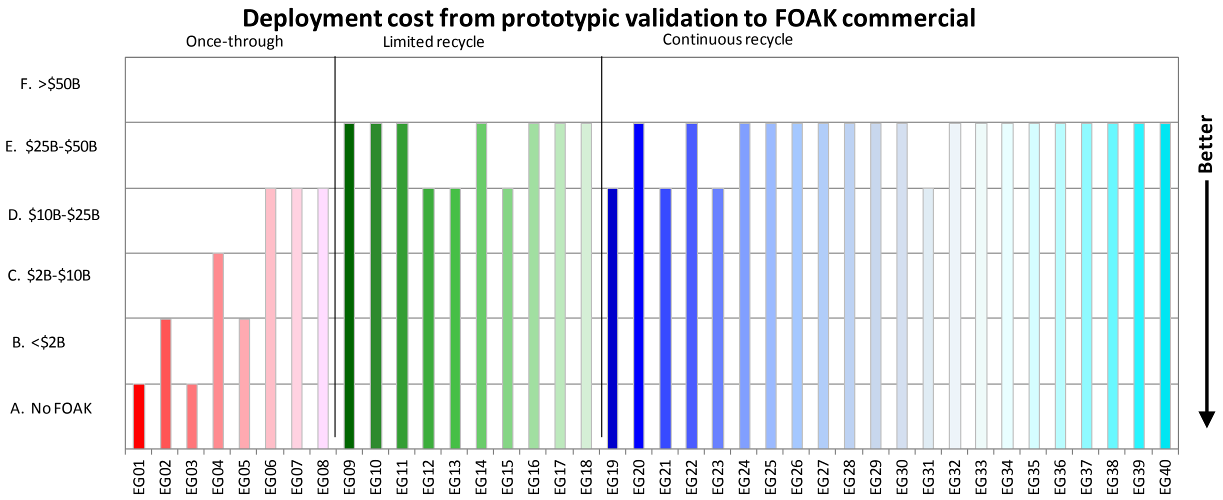


Figure D-2.18.1. Metric Data for Deployment Cost from Prototypic Validation to FOAK Commercial for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Metric Observations

The deployment cost metric is a metric for one of the "challenge" criteria as described in Appendix A, for which the Basis of Comparison has the lowest level of "challenge." As a consequence, this is a metric for which there are no promising Evaluation Groups. All fuel cycle options with the exception of the currently deployed Basis of Comparison EG01 and EG03 all require some deployment cost and by definition are in lower performing bins. However, based on a ranking of the Evaluation Groups by bin, observations of the Evaluation Groups based on the deployment cost metric data are as follows:

- EG01 and EG03 have examples that are currently deployed beyond FOAK and therefore have no deployment cost. These are included in the metric Bin A (already deployed).
- Highly ranked fuel cycle Evaluation Groups include fuel cycles that require only fuels development including once-through fuel cycles that can use existing thermal reactors with uranium fuels that can achieve higher burnups, EG02, and thorium fuels, EG05. These fuel cycles only require qualification that can largely be performed with existing facilities. These correspond to Bin B (<$2B to achieve a FOAK deployment).
- EG04 is the highest ranking fuel cycle Evaluation Group that utilizes fast reactors and ranks highly overall for this metric. This results because this option represents a once-through fuel cycle that requires primarily only the reactor system and is the only fuel cycle in Bin C ($2B-$10B for FOAK deployment).
- All other EGs require deployment of multiple systems and are included in Bin D ($10B - $25B) and Bin E ($25B - $50B) to achieve a FOAK deployment.

D-2.19 Compatibility with the Existing Infrastructure

Approach for determining metric data

The approach for determining the compatibility with the existing infrastructure metric data for each Evaluation Group uses an approach based on comparing the processes each Evaluation Group with those of EG01, the Basis of Comparison. Since the primary infrastructure associated with each fuel cycle is based on the reactors, fuel manufacturing and reprocessing processes, the approach compares these processes to the Basis of Comparison using the fuel cycle process to Evaluation Group mapping table in Appendix C-4. Guidelines for considering what is existing versus new infrastructure are as follows:

- Existing infrastructure defined by reactors processes RX-0, RX-1, and fuel fabrication FF-1
- New infrastructure defined by reactor processes RX-2, RX-3, and RX-4, fuel fabrication processes FF-2, FF-3, FF-4, FF-5), and reprocessing processes RP-1, RP-2, and RP-3.
- For Evaluation Groups that have more than one reactor process, the fraction of that process is determined by using the relative share of power generation by the reactor process type based on the data from the Analysis Example for that Evaluation Group as discussed in Appendix B.

The combination of the fuel cycle process data to determine the bin for each Evaluation Group is based on comparing these fuel cycle processes and selecting a bin based on the bin descriptions and the basis for bin selection defined in Table D-2.19.1.

Table D-2.19.1. Compatibility with the Existing Infrastructure Bin Descriptions and the Basis for the Selection of a Bin.

Bin	Bin Descriptions	Basis for selection of bin
A. Requires Nearly No New Infrastructure	The fuel cycle option fully utilizes the existing infrastructure as represented by the fuel cycle basis for comparison, needing very little additional infrastructure to deploy the fuel cycle. Estimate is that 90% or more of the required infrastructure can be based on existing infrastructure. This bin contains the Basis of Comparison.	Uses more than 90% of the existing infrastructure
B. Requires Some New Infrastructure	The fuel cycle option utilizes mostly components of the existing infrastructure and may require some additional infrastructure components. Estimate is that more than 50% (but less than 90%) of the required infrastructure can be based on existing infrastructure.	Uses existing and new infrastructure More than 50 % of existing reactor types May require reprocessing/new fab type facilities
C. Requires Mostly New Infrastructure	The fuel cycle option utilizes some components of the existing infrastructure and requires mostly additional infrastructure components. Estimate is that less than 50% (but more than 10%) of the required infrastructure will be based on existing infrastructure.	Uses existing and new infrastructure Less than 50% of existing reactor types May require reprocessing/new fab type facilities
D. Requires Almost Entirely New Infrastructure	The fuel cycle option utilizes few or none of the components of the existing infrastructure and requires mostly new infrastructure components for deployment. Estimate is that less than 10% of the required infrastructure can be based on existing infrastructure.	Uses less than 10% of the existing infrastructure

Metric data

The compatibility with the existing infrastructure metric data for each Evaluation Group is provided in Table D-2.19.2.

Table D-2.19.2. Metric Data for Compatibility with the Existing Infrastructure for the 40 Evaluation Groups.

Evaluation Group	Metric Data
EG01	Bin A
EG02	Bin A
EG03	Bin C
EG04	Bin D
EG05	Bin B
EG06	Bin D
EG07	Bin D
EG08	Bin D
EG09	Bin D
EG10	Bin D
EG11	Bin D

EG12	Bin C
EG13	Bin B
EG14	Bin C
EG15	Bin B
EG16	Bin B
EG17	Bin B
EG18	Bin B
EG19	Bin C
EG20	Bin C
EG21	Bin B
EG22	Bin B
EG23	Bin D
EG24	Bin D
EG25	Bin D
EG26	Bin D
EG27	Bin D
EG28	Bin D
EG29	Bin C
EG30	Bin C
EG31	Bin C
EG32	Bin C
EG33	Bin C
EG34	Bin C
EG35	Bin B
EG36	Bin B
EG37	Bin C
EG38	Bin C
EG39	Bin B
EG40	Bin B

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.19.1 (note that the same data is provided in the second column of Table D-2.19.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

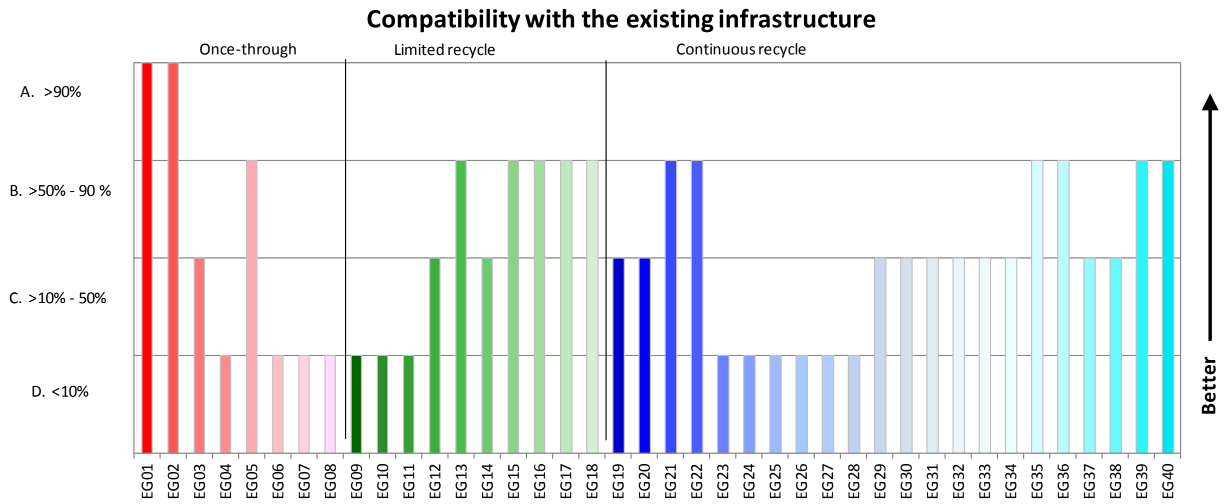


Figure D-2.19.1. Metric Data for the Compatibility with the Existing Infrastructure Metric for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Metric Observations

The infrastructure compatibility metric is a metric for one of the "challenge" criteria as described in Appendix A, for which the Basis of Comparison has the lowest level of “challenge.” As a consequence, this is a metric for which there are no promising Evaluation Groups. All fuel cycle options with the exception of the currently deployed Basis of Comparison EG01 and EG02 all require some new supporting infrastructure and by definition are in lower performing bins. However, based on a ranking of the Evaluation Groups by bin, observations of the Evaluation Groups based on the compatibility with the existing infrastructure metric data are as follows:

- EG01 and EG02, which could be implemented with existing reactors with higher burnup fuels, have the highest compatibility with the existing infrastructure. These are included in Bin A, > 90% use of existing infrastructure.
- Evaluation Groups that can mostly use the existing reactor types with advanced fuels or the additional of recycle to the existing reactor types results in fuel cycles that are mostly compatible with the existing infrastructure. These EGs (EG05, EG13, EG15, EG16 - EG18, EG21, EG22, EG35, EG36, EG39, EG40) are included in Bin B, 50% - 90% use of existing infrastructure.
- Evaluation Groups that introduce new reactor types with the purpose of burning wastes from existing reactor types, rather than generating a substantial fraction of the power, are also mostly compatible with existing infrastructure since they continue to utilize the existing reactor types. This includes EG03, EG12, EG14, EG19, EG20, EG29 – EG34, EG37, EG39 included in Bin C, 10% - 50% use of existing infrastructure.
- Evaluation Groups that have little or no use of existing reactor types have the least compatibility with existing infrastructure including EG04, EG06-EG11, EG23 – EG28 and use less than 10% of existing infrastructure (Bin D).

D-2.20 Existence of Regulations for the Fuel Cycle and Familiarity with Licensing

Approach for determining metric data

The approach for determining the existence of regulations for the fuel cycle and familiarity with licensing metric data for each Evaluation Group used an approach based on using the lowest bin of all fuel cycle processes that compose the evaluation group. In Appendix C-7, fuel cycle process data is provided for each fuel cycle process and using the fuel cycle process to Evaluation Group mapping table in Appendix C-4, the fuel cycle process data can be combined to obtain the overall metric data for the Evaluation Group based on the overall lowest bin, which is selected as the metric data for the Evaluation Group.

Metric data

The bin descriptions for the development cost bins in this table are defined in Appendix C and are repeated in Table D-2.20-1.

Table D-2.20.1. Existence of Regulations and Familiarity with Licensing Bin Descriptions.

Bin	**Bin Descriptions for Existence of Regulations and Familiarity with Licensing**
A. Demonstrated U.S. Regulations/Familiarity	U.S. Regulations and regulatory experience exists for fuel cycle facility types that have been demonstrated through issuing operating licenses. This bin contains the Basis of Comparison.
B. Limited U.S. Regulations/Familiarity	U.S. Regulations and regulatory experience exists for fuel cycle facility types but have not been demonstrated through issuing operating licenses. Regulatory authorities have some previous experience with key fuel cycle components, but may not have licensed these facility types.
C. No U.S. Regulations/Familiarity	No U.S. regulatory experience for fuel cycle facility types and use, but international regulatory experience exists through licensing of operating facilities.
D. No Regulations/Familiarity	No regulatory experience exists for key fuel cycle facility types and use.

The Metric Data for the existence of regulations for the fuel cycle and familiarity with licensing metric for each Evaluation Group is provided in Table D-2.20.2.

Table D-2.20.2. Metric Data for the Existence of Regulations for the Fuel Cycle and Familiarity with Licensing Metric for the 40 Evaluation Groups.

Evaluation Group	**Metric Data**
EG01	Bin A
EG02	Bin A
EG03	Bin B
EG04	Bin C
EG05	Bin D
EG06	Bin D
EG07	Bin D
EG08	Bin D
EG09	Bin D
EG10	Bin D
EG11	Bin D
EG12	Bin C
EG13	Bin C
EG14	Bin C
EG15	Bin C
EG16	Bin D
EG17	Bin D
EG18	Bin D
EG19	Bin C
EG20	Bin D
EG21	Bin C
EG22	Bin D
EG23	Bin C
EG24	Bin D
EG25	Bin D
EG26	Bin D
EG27	Bin D
EG28	Bin D

EG29	Bin C
EG30	Bin D
EG31	Bin C
EG32	Bin D
EG33	Bin D
EG34	Bin D
EG35	Bin D
EG36	Bin D
EG37	Bin D
EG38	Bin D
EG39	Bin D
EG40	Bin D

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.20.1 (note that the same data is provided in the second column of Table D-2.20.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

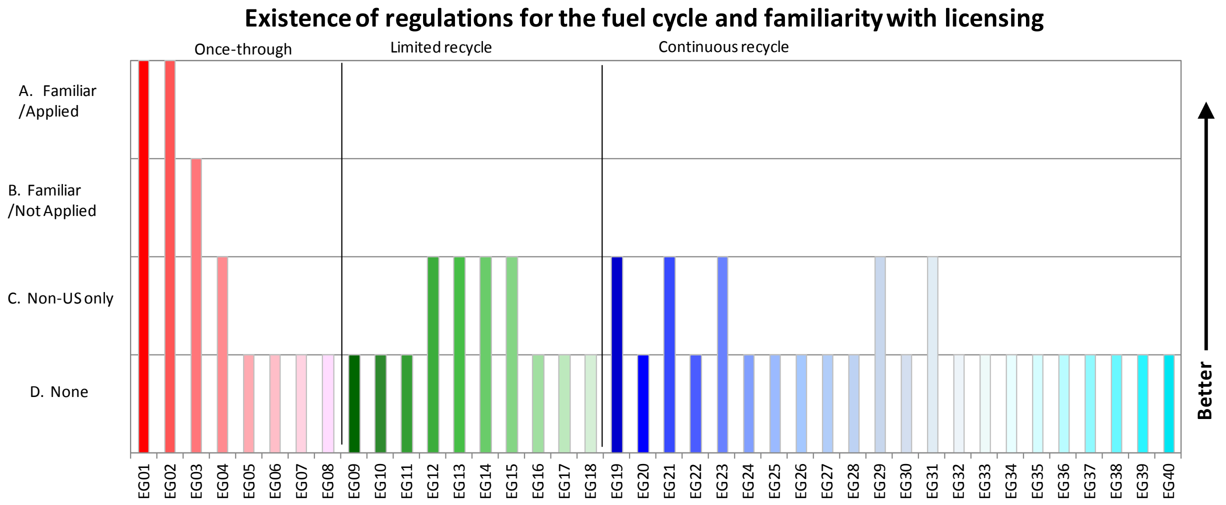


Figure D-2.20.1. Metric Data for Existence of Regulations for the Fuel Cycle and Familiarity with Licensing for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Metric Observations

The existence of regulations for the fuel cycle and familiarity with licensing metric is a metric for one of the "challenge" criteria as described in Appendix A, for which the Basis of Comparison has the lowest level of “challenge.” As a consequence, this is a metric for which there are no promising Evaluation Groups. All fuel cycle options with the exception of the currently deployed Basis of Comparison EG01 and EG02 all require new regulations and licensing frameworks and by definition are in lower performing bins. However, based on a ranking of the Evaluation Groups by bin, observations of the Evaluation Groups based on the existence of regulations for the fuel cycle and familiarity with licensing metric data are as follows:

- U.S. Regulations and familiarity exist for fuel cycles that have been deployed, which include Evaluation Groups that can use similar technologies to the Basis of Comparison EG01and EG02. These are included in Bin A.

- EG03 that utilizes a once-through thermal reactor with natural uranium (such as CANDU), can utilize regulations largely based on existing regulations and have familiarity based on recent licensing activities. This EG is included in Bin B.
- Non-US, International regulations and familiarity exist for fuel cycles that recycle Pu-containing fuels (e.g. MOX) and fast reactors. These include EG04, EG12-EG15, EG19, EG21, EG23, EG29, and EG31, which are included in Bin C.
- The remainder of the EGs include technologies for which there are essentially no existing regulations or familiarity with licensing in the U.S. or internationally, these are included in Bin D.

D-2.21 Existence of Market Incentives and/or Barriers to Commercial Implementation of Fuel Cycle Processes

Overview

The determination of the Metric Data for the Existence of Market Incentives and/or Barriers to Commercial Implementation of Fuel Cycle Processes metric, or the "Market Metric", examines the market factors for each Evaluation Group under consideration. Since each Evaluation Group is defined by the processes it contains and requires, the Market Metric Working Group (a subset of the EST) analyzed market factors related to individual processes and then identified the processes included in each Evaluation Group. This provided an efficient and effective methodology and facilitated consistency in the analysis of Evaluation Groups. This approach included the following steps:

- Identify fuel cycle processes;
- Analyze the market considerations associated with each identified process;
- Assign processes to Evaluation Groups;
- Development of metric data; and
- Summarize results.

Each of these steps is discussed below.

A. Identify Fuel Cycle Processes

The list of identified processes that could generate unique assessments for the Market Metric were identified. Table D-2.21.1 provides this listing.

Table D-2.21.1. Identified Fuel Cycle Processes.

Process Code	**Description**
FS-1	Fuel supply - Mined uranium
FS-2	Fuel supply - Mined thorium
UE-1	Uranium enrichment , < 5 wt. %
UE-2	Uranium enrichment >5 wt.%
FF-1	Fuel fabrication with unirradiated uranium
FF-2	Advanced fuel fabrication (e.g., unirradiated thorium; uranium/thorium; Recycle with RU/Pu)
RX-1	Reactor: Thermal-critical with traditional fuels
RX-2	Reactors: Thermal-critical with advanced fuels
RX-3	Reactors: Fast-critical
RX-4	Reactors: Sub-critical
RP-1	Reprocessing with RU/Pu product
RP-2	Reprocessing with RU/TRU product
RP-3	Reprocessing with U3/Th/TRU products
FF-3	Recycle fuel fabrication with RU/Pu
FF-4	Recycle fuel fabrication with RU/TRU
FF-5	Recycle fuel fabrication with U3/Th/TRU
RX-1r	Reactor with recycle fuel: Thermal-critical
RX-2r	Reactor with recycle fuel: Thermal-critical with advanced fuels
RX-3r	Reactor with recycle fuel: Fast-critical
RX-4r	Reactor with recycle fuel: Sub-critical
ST-1	Storage of nuclear materials
TR-1	Transport of nuclear materials
DS-1	Disposal of DU
DS-2	Disposal of Discharge Fuel
DS-3	Disposal of HLW

B. Analyze the Market Considerations Associated with Each Identified Process

Capital at risk and market drivers were examined for each identified process. To facilitate this analysis, questions were formulated for the capital at risk and market incentives described in Appendix C. Nearly all of the questions were structured to facilitate a response of “Yes/Likely”, “Maybe/Uncertain”, or “No/Unlikely”, simplifying the process of aggregating the data into meaningful results.

For the capital at risk factor, six questions were asked for each process:

1. Capital Investment: Will the investment of substantial new capital (beyond the cost of replacing existing / aging facilities) be required to implement this process?
2. Payback Period: Is the payback period for investment greater than 20 years?
3. Scaling/penetration: Does the plausible deployment scenario require new large scale facilities or numerous small-scale facilities?
4. Will the process benefit from existing facilities / infrastructure?
5. Technical Complexity: Is the process likely to be technically complex and tightly integrated with other processes?
6. Flexibility / forward compatibility: Is investment in this process directly applicable to numerous other Evaluation Groups, or to another existing industrial process?

As an illustration, Table D-2.21.2 provides the summary for three of the reprocessing or “RP” processes. Each of these processes includes an investment in reprocessing facilities and infrastructure.

Table D-2.21.2. Illustrative Example - RP Process Results for Capital at Risk.

Capital At Risk Related Questions	Reprocessing with RU/Pu product RP-1	Reprocessing with RU/TRU product RP-2	Reprocessing with U3/Th/TRU products RP-3
1. Capital Investment: Will the investment of substantial new capital (beyond the cost of replacing existing / aging facilities) be required to implement this process?	Yes / Likely	Yes / Likely	Yes / Likely
2. Payback Period: Is the payback period for investment greater than 20 years?	Maybe/ Uncertain	Maybe/ Uncertain	Maybe/ Uncertain
3. Scaling/Penetration: Does the plausible deployment scenario require new large scale facilities or numerous small-scale facilities?	Yes / Likely	Yes / Likely	Yes / Likely
4. Will the process benefit from existing facilities / infrastructure?	No / Unlikely	No / Unlikely	No / Unlikely
5. Technical Complexity: Is the process likely to be technically complex and tightly integrated with other processes?	Yes / Likely	Yes / Likely	Yes / Likely
6. Flexibility / Forward Compatibility: Is investment in this process directly applicable to numerous other Evaluation Groups, or to another existing industrial process?	Yes / Likely	Yes / Likely	Yes / Likely

Of the six questions, question #1 proved to be the most influential. Responses tended to be correlated with the questions related to scaling and penetration. The questions related to payback period proved to be a challenge. While an important consideration, payback prospects will be influenced by project-specific inputs which cannot be estimated. In addition, the responses to other questions did not provide meaningful differentiation across processes.

For the market incentives and drivers factor, five questions were asked for each process. All but question #5 required a response of “Yes/Likely”, “Maybe/Uncertain,” or “No/Unlikely”. Question #5 required the selection of one of four levels of government participation.

1. Industry Structure: Are significant changes to the industry/industry structure required?
2. Market systems for cost recovery: Are there likely to be market mechanisms in place to facilitate payment for the outputs?
3. Market Distortions (Negative): Are there laws or regulations that are likely to inhibit the development of this process?
4. Market Distortions (Positive): Are there laws or regulations that are likely to encourage the development of this process?
5. How Much Participation will be required by the Federal government?
    - Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations.
    - Significant: The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations.
    - Limited: The government may need to induce investment through new financial or regulatory incentives.

- De minimus: Routine / ordinary investment, incentives or actions by the Federal government is required.

The Market Metric Working Group found that questions 1 through 4 provided the information needed to answer question #5. Table D-2.21.3 provides as example the summary for the “RP” processes for the market driver factors.

Table D-2.21.3. Illustrative Example - RP Process Results for Market Driver Factors.

Market Incentives and Drivers Factor	Reprocessing with RU/Pu product RP-1	Reprocessing with RU/TRU product RP-2	Reprocessing with U3/Th/TRU products RP-3
1. Industry Structure: Are significant changes to the industry/industry structure required?	Yes / Likely	Yes / Likely	Yes / Likely
2. Market Systems for Cost Recovery: Are there likely to be market mechanisms in place to facilitate payment for the outputs?	No / Unlikely	No / Unlikely	No / Unlikely
3. Market Distortions (negative): Are there laws or regulations that are likely to inhibit the development of this process?	Yes / Likely	Yes / Likely	Yes / Likely
4. Market Distortions (positive): Are there laws or regulations that are likely to encourage the development of this process?	No / Unlikely	No / Unlikely	No / Unlikely
5. How Much Participation will be Required by the Federal Government?	Significant	Highly Significant	Highly Significant

In this illustration, the fuel cycles options requiring reprocessing would require significant investments with highly uncertain return profiles; markets and markets mechanisms do not exist for the inputs and outputs of reprocessing facilities, and market distortions currently exist that do not encourage waste minimization. Therefore, it is reasonable to conclude that the Federal government would be required to participate in the industry in order to drive demand. For reprocessing processes, this role of the Federal government is expected to be significant or highly significant over the long term. The summaries for all of the 22 processes used in the current evaluation are provided in Table D-2.21.4. For each process, the detailed responses to the questions supporting the summary table are provided in Table D-2.21.5 to Table D-2.21.26.

Table D-2.21.4. Summary for all Processes.

FACTOR	Fuel supply - Mined uranium	Fuel supply - Mined thorium	Uranium enrichment , < 5 wt. %	Uranium enrichment >5 wt.%, < 20 wt. %	Fuel fabrication with unirradiated uranium	Advanced fuel fabrication (e.g., unirradiated thorium; uranium/thorium; Recycle with RU/Pu)	Reactor: Thermal-critical with traditional fuels	Reactors: Thermal-critical with advanced fuels	Reactors: Fast-critical	Reactors: Sub-critical	Reprocessing with RU/Pu product	Reprocessing with RU/TRU product	Reprocessing with U3/Th/TRU products	Recycle fuel fabrication with RU/Pu	Recycle fuel fabrication with RU/TRU	Recycle fuel fabrication with U3/Th/TRU	Reactor with recycle fuel: Thermal-critical	Reactor with recycle fuel: Thermal-critical with advanced fuels	Reactor with recycle fuel: Fast-critical	Reactor with recycle fuel: Sub-critical	Storage of nuclear materials	Transport of nuclear materials
	FS-1	FS-2	UE-1	UE-2	FF-1	FF-2	RX-1	RX-2	RX-3	RX-4	RP-1	RP-2	RP-3	FF-3	FF-4	FF-5	RX-1r	RX-2r	RX-3r	RX-4r	ST-1	TR-1
Capital Investment: Will the investment of substantial new capital (beyond the cost of replacing existing / aging facilities) be required to implement this process?	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Yes / Likely	No / Unlikely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely
Payback Period: Is the payback period for investment greater than 20 years?	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	Not Applicable
Scaling/Penetration: Does the plausible deployment scenario require new large scale facilities or numerous small-scale facilities?	No / Unlikely	No / Unlikely	Maybe / Uncertain	Maybe / Uncertain	No / Unlikely	Yes / Likely	No / Unlikely	No / Unlikely	Maybe / Uncertain	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely	No / Unlikely	Maybe / Uncertain	Yes / Likely	No / Unlikely	No / Unlikely
Will the process benefit from existing facilities / infrastructure?	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Maybe / Uncertain	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Yes / Likely	No / Unlikely	No / Unlikely	Yes / Likely	Yes / Likely	Maybe / Uncertain	No / Unlikely	Yes / Likely	Yes / Likely
Technical Complexity: Is the process likely to be technically complex and tightly integrated with other processes?	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Maybe / Uncertain	No / Unlikely	Maybe / Uncertain	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Maybe / Uncertain	Yes / Likely	Yes / Likely	No / Unlikely	Maybe / Uncertain	Yes / Likely	Yes / Likely	Not Applicable	Yes / Likely
Flexibility / Forward Compatibility: Is investment in this process directly applicable to numberous other Evaluation Groups, or to another existing industrial process?	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely
Industry Structure: Are significant changes to the industry/industry structure required?	No / Unlikely	Maybe / Uncertain	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Maybe / Uncertain	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely	Yes / Likely	Yes / Likely	No / Unlikely	No / Unlikely	Maybe / Uncertain	Yes / Likely	Maybe / Uncertain	No / Unlikely
Market Systems for Cost Recovery: Are there likely to be market mechanisms in place to faciliate payment for the outputs?	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely	No / Unlikely	No / Unlikely	Yes / Likely	No / Unlikely	No / Unlikely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely
Market Distortions (Negative): Are there laws or regulations that are likely to inhibit the development of this process?	No / Unlikely	No / Unlikely	No / Unlikely	Maybe / Uncertain	No / Unlikely	Maybe / Uncertain	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Yes / Likely	Yes / Likely	Yes / Likely	Maybe / Uncertain	Maybe / Uncertain	Maybe / Uncertain	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Maybe / Uncertain	Maybe / Uncertain
Market Distortions (Positive): Are there laws or regulations that are likely to encourage the development of this process?	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Maybe / Uncertain	Maybe / Uncertain	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely
How Much Participation will be Required by the Federal Government?	Deminimus	Deminimus	Deminimus	Deminimus	Deminimus	Limited	Deminimus	Limited	Significant	Significant	Significant	Highly Significant	Highly Significant	Limited	Highly Significant	Highly Significant	Deminimus	Limited	Significant	Significant	Limited	Deminimus

Table D-2.21.5. Responses for Process FS-1, Fuel Supply – Mined Uranium.

Process:	FS-1
Description	Fuel supply - Mined uranium

Key Market-Related Issues

There are no significant market-related issues for mined uranium as a fuel supply. Existing infrastructure and facilities are in place, industrial infrastructure is well-established, and there are existing, functioning markets for uranium. Several Evaluation Groups require significantly less mined Uranium than the current nuclear fuel cycle (per GWe-yr), which could lead to excess uranium mining capacity; this could be viewed as a disincentive for the fuel cycle, but given the likely transition period the industry would have sufficient time to adjust (and they have recent experience in downsizing).

If there are Evaluation Groups that required significantly greater amounts (per GWe-yr) of mined uranium, additional facilities may be required -- but those facilities would enter an existing market, so the "market considerations" would be minimal.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**No / Unlikely**	See "Key Market-Related Issues" above
Is the payback period for investment greater than 20 years?	**Not Applicable**	See "Key Market-Related Issues" above
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	See "Key Market-Related Issues" above
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**No / Unlikely**	See "Key Market-Related Issues" above
Industry Structure		
Are significant changes to the industry required?	**No / Unlikely**	See "Key Market-Related Issues" above
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**No / Unlikely**	See "Key Market-Related Issues" above
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	For most processes "upstream" of the reactor, commercial markets already exist to provide the "inputs" to nuclear power production. Even under significant departures from the current fuel cycle, it is likely that the existing commmercial and industrial actors will continue to be major players in providing these front-end processes and materials.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	See "Key Market-Related Issues" above
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	See "Key Market-Related Issues" above
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial	**Yes / Likely**	Many evaluation groups utilize mined uranium
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Deminimus**	See "Key Market-Related Issues" above

Table D-2.21.6. Responses for Process FS-2, Fuel Supply, Mined Thorium.

Process:	FS-2
Description	Fuel supply - Mined thorium

Key Market-Related Issues

Thorium fuel resources will need to be developed; currently thorium mining infrastructure is underdeveloped. However, the mining technologies for rare earths are well known and can be applied to thorium acquistion. It has been suggested that thorium can be extracted with very low effort and cost as a bi-product from other rare-earth mining activities using facilities and infrastructure used for other minerals. In addition, thorium fuel cycles are inherently a breeding cycle and the quantity needed is relatively small. The assessments below assume that this is the case.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**No / Unlikely**	If the quantity of thorium needed is sufficiently large, may need new thorium-specific mines. If only small quantities are needed (as is the case for all of the EGs being considered), this can be done at an incremental/insignificant cost with coproduction from existing rare-earth operations (assuming that such operations exist).
Is the payback period for investment greater than 20 years?	**Not Applicable**	See "Key Market-Related Issues" above
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	See "Key Market-Related Issues" above
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**No / Unlikely**	See "Key Market-Related Issues" above
Industry Structure		
Are significant changes to the industry required?	**Maybe / Uncertain**	Thorium extraction is a new process. Changes in the industry to start treating it as a resource rather than a waste product will be required, and it is not clear whether structural changes will be required.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**No / Unlikely**	See "Key Market-Related Issues" above
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	For most processes "upstream" of the reactor, commercial markets already exist to provide the "inputs" to nuclear power production. Even under significant departures from the current fuel cycle, it is likely that the existing commmercial and industrial actors will continue to be major players in providing these front-end processes and materials.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	See "Key Market-Related Issues" above
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	See "Key Market-Related Issues" above
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Many evaluation groups utilize mined thorium.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Deminimus**	See "Key Market-Related Issues" above

Table D-2.21.7. Responses for Process UE-1, Uranium Enrichment, < 5%.

Process: UE-1

Description Uranium enrichment , < 5 wt. %

Key Market-Related Issues

Enrichment is currently a market-driven activity, with established markets and players. The enrichment capacity required will vary by evaluation group. In some cases only 8% of the capacity currently available for US fuels will be required (EG37), while in other cases enrichment demands may be significantly higher than what is currently available in the commercial nuclear industry (EG02 and EG05). Given the expected transition times, even for fuel cycles that ultimately need more enrichment capacity can begin with the current capacity, and it is likely that the industry can expand/adjust to meet the anticipated needs.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**No / Unlikely**	Capacity currently exists; if additional capacity is needed it can be addresssed over time by current industry players without the need for a significant investment.
Is the payback period for investment greater than 20 years?	**Not Applicable**	
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	Facilities are modular and technology is well demonstrated.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**No / Unlikely**	Enrichment is not tightly integrated with other processes.
Industry Structure		
Are significant changes to the industry required?	**No / Unlikely**	Current industry can support capacity expansion and technology improvements. Such changes would be driven by demand.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Maybe / Uncertain**	New facilities may be required, depending on the capacity needs of the evaluation group. Consider this on an EG-by-EG basis.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	For most processes "upstream" of the reactor, commercial markets already exist to provide the "inputs" to nuclear power production. Even under significant departures from the current fuel cycle, it is likely that the existing commmercial and industrial actors will continue to be major players in providing these front-end processes and materials.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capability		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Enrichment product (SWUs) can be utilized in any EG using enriched uranium.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Deminimus**	Given existence of functioning market, changes in this process are likely to be incremental and market driven.

Table D-2.21.8. Responses for Process UE-2, Uranium Enrichment, > 5%.

Process: UE-2

Description Uranium enrichment >5 wt.%, < 20 wt. %

Key Market-Related Issues

It is possible to enrich up to 20 wt.% using essentially the same facilities and infrastucture that currently exists, which means that there would be no need for an entirely new set of facilities and infrastucture. Capital at risk would be low, and other market drivers would be largely the same as for UE-1. It is possible that higher enrichment levels lead to more constraints or concerns on the trasportation side. If so, there may affect the composition of the market and location of new capacity.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**No / Unlikely**	Capacity currently exists; if additional capacity is needed it can be addresssed over time by current industry participants without the need for a significant investment.
Is the payback period for investment greater than 20 years?	**Not Applicable**	
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	Facilities are modular and technology is well demonstrated.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**No / Unlikely**	Enrichment is not tightly integrated with other processes.
Industry Structure		
Are significant changes to the industry required?	**No / Unlikely**	Current industry can support capacity expansion and technology improvements. Such changes would be driven by demand.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Maybe / Uncertain**	New facilities may be required, depending on the capacity needs of the evaluation group.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	For most processes "upstream" of the reactor, commercial markets already exist to provide the "inputs" to nuclear power production. Even under significant departures from the current fuel cycle, it is likely that the existing commmercial and industrial actors will continue to be major players in providing these front-end processes and materials.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**Maybe / Uncertain**	There is, at least a perception that enriching above 5% is a challenge -- it was considered as one of the potential "constraints," but then determined that no such legal constraint exists. As suggested above, there may be transportation-related issues associated with higher enrichment levels.
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial	**Yes / Likely**	Enrichment product (SWUs) can be utilized in any EG using enriched uranium.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Deminimus**	Given existence of functioning market, changes in this process are likely to be incremental and market driven.

Table D-2.21.9. Responses for Process FF-1, Fuel Fabrication with Unirradiated Uranium.

Process:	FF-1
Description	Fuel fabrication with unirradiated uranium

Key Market-Related Issues

For unirradiated fuels, the required processes are established and are an existing commercial process. Market considerations are similar to those for uranium mining (UE-1) and Enrichment to less than 5% (UE-1).

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	No / Unlikely	See "Key Market-Related Issues" above
Is the payback period for investment greater than 20 years?	Not Applicable	
Will the process benefit from existing facilities / infrastructure?	Yes / Likely	See "Key Market-Related Issues" above
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	No / Unlikely	See "Key Market-Related Issues" above
Industry Structure		
Are significant changes to the industry required?	No / Unlikely	See "Key Market-Related Issues" above
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	No / Unlikely	See "Key Market-Related Issues" above
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	Yes / Likely	For most processes "upstream" of the reactor, commercial markets already exist to provide the "inputs" to nuclear power production. Even under significant departures from the current fuel cycle, it is likely that the existing commmercial and industrial actors will continue to be major players in providing these front-end processes and materials.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	No / Unlikely	See "Key Market-Related Issues" above
Are there laws or regulations that are likely to encourage the development of this process?	No / Unlikely	See "Key Market-Related Issues" above
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	Yes / Likely	See "Key Market-Related Issues" above
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	Deminimus	Given existence of functioning market, changes in this process are likely to be incremental and market driven.

Table D-2.21.10. Responses for Process FF-2, Advanced Fuel Fabrication.

Process: FF-2

Description Advanced fuel fabrication (e.g., unirradiated thorium; uranium/thorium; Recycle with RU/Pu)

Key Market-Related Issues

Note that this process includes fuel fabrication with unirradiated thorium, and uranium and thorium together. The same assessment applies to fuel fabrication with recycle RU/Pu (FF-3). These fuels have not been produced commercially in the US, and fuel fabrication with thorium will require both new designs and new facilities.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to	**Yes / Likely**	Depending on the thermal reactor design, there might be significant deviation from the current fuel fabrication approach.
Is the payback period for investment greater than 20 years?	**No / Unlikely**	Fuel fabrication is currenty conducted on a commercial basis, so fabrication with other materials is likely to enter into that same market, with an commensurate commercial project payback period.
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	It is likely that new facilities will resemble and benefit from existing facilities and infrastructure for fuel fabrication.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Maybe / Uncertain**	Fuel fabrication and reactor type are integrated/linked. Need for inventory management "starts" here.
Industry Structure		
Are significant changes to the industry required?	**No / Unlikely**	Buyers, sellers, and market mechanisms for fabricated fuels will not likely change with a move to thorium-based or advanced fuels.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Yes / Likely**	New fuel fabrication facilities will be required.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	For most processes "upstream" of the reactor, commercial markets already exist to provide the "inputs" to nuclear power production. Even under significant departures from the current fuel cycle, it is likely that the existing commmercial and industrial actors will continue to be major players in providing these front-end processes and materials.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**Maybe / Uncertain**	Uncertain since this process has not been introduced in the US.
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Investments in advanced fuel fabrication will likely apply to multiple EG's.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Limited**	Some incentives may be required to induce investment in the fabrication capacity needed to support new reactors. This investment needs to be made simultaneously with investment in generation. This intoduces financial risk as capacity investments will be required in advance of demonstrated demand.

Table D-2.21.11. Responses for Process RX-1, Thermal Critical Reactor with Traditional Fuels.

Process: RX-1

Description Reactor: Thermal-critical with traditional fuels

Key Market-Related Issues

Many EGs use LWR as the thermal-critical reactors. Most of those are very similar to the LWRs in the basis for comparison.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**No / Unlikely**	The process is similar to LWR's in operation today. Aging facilities will be replaced but singificant new investment will not be required.
Is the payback period for investment greater than 20 years?	**Not Applicable**	
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	Existing LWR technologies can be used for stages of the system.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**No / Unlikely**	Multi-stage systems will introduce greater complexity.
Industry Structure		
Are significant changes to the industry required?	**No / Unlikely**	Multi-stage systems will require changes in the industry.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**No / Unlikely**	Multi-stage systems will require new large scale facilities.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	The main "output" of reactors processes is electricity, for which there is a market.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Investments in this process will likely apply to multiple EG's.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Deminimus**	This will depend on the Evaluation Group. However, the extent of government intervention will be reflected in the Evaluation Groups that include reprocessing.

Table D-2.21.12. Responses for Process RX-2, Thermal Critical Reactor with Advanced Fuels.

Process:	RX-2
Description	Reactors: Thermal-critical with advanced fuels

Key Market-Related Issues

LWRs and other thermal systems with higher burnups than the basis for comparison. Transitioning to significantly higher burnup LWRs will entail the qualification of higher enrichment fuels and might involve the use of enrichments higher than what is currently available in the commercial nuclear power industry. Deploying thermal systems different from the current LWRs in the U.S. will entail a transition from LWRs to the new systems.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**Yes / Likely**	See "Key Market-Related Issues" above
Is the payback period for investment greater than 20 years?	**Maybe / Uncertain**	For some EG, payback period will be less than 20 yrs. For others it is not likely.
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Maybe / Uncertain**	May need to consider this on an EG level.
Industry Structure		
Are significant changes to the industry required?	**No / Unlikely**	
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**No / Unlikely**	Reactor size/scaling/penetration will be similar to that for the current fuel cycle.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	The main "output" of reactors processes is electricity, for which there is a market.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Limited**	If fuels are available, commercial utilities would not need a lot of incentive or government investments to use those fuels (esp. where existing facilities and be used with slight modification); May need to consider differences on an EG level.

Table D-2.21.13. Responses for Process RX-3, Fast Critical Reactors.

Process: RX-3

Description Reactors: Fast-critical

Key Market-Related Issues

Fast spectrum systems are required. Deploying fast-spectrum systems in the U.S. will entail a transition from LWRs to the new systems. At the equilibrium state, these fast-spectrum systems do not require fuel enrichment. However, for the startup of such systems, enriched uranium fuel will be required. No operating commercial reactors of this type exist in the US. There is some (non-commercial) experience at the demonstration process level in the US and some FOAK commercial systems in other countries. ~20 have been built world-wide with mixed results. Economics suggest that large-scale reactors will be prefereable (at least initially). Very different fuel assemblies required (than for thermal-critical), will operate with higher burnup and produce higher activity waste products. Typically associated with reprocessing but not always. Best way to get to a breeding cycle. Fast reactors are more homogeneous and less sensitive than thermal-critical to what they use.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**Yes / Likely**	See "Key Market-Related Issues" above
Is the payback period for investment greater than 20 years?	**Maybe / Uncertain**	
Will the process benefit from existing facilities / infrastructure?	**Maybe / Uncertain**	
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Yes / Likely**	
Industry Structure		
Are significant changes to the industry required?	**Maybe / Uncertain**	
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Maybe / Uncertain**	Large scale facilities are expected but it is unclear whether facilities larger than those currently utilized will be required?
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	The main "output" of reactors processes is electricity, for which there is a market.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Only one EG is expected to utilize this process.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Significant**	

Table D-2.21.14. Responses for Process RX-4, Sub-critical Reactors.

Process: RX-4

Description Reactors: Sub-critical

Key Market-Related Issues

The hurdles for subcritical systems are significant, fuels and the distinction between thermal and fast are secondary given the main challenges. Everything has to be built from scratch. Externally driven systems will be required or an ADS system will be required for stage 1. Therefore, this process will require an investment of significant capital into an uncertain market. These reactors have the greatest market barriers of the 4 types of reactors (as well as the largest technical hurdles?). Motivation is resource efficiency without enrichment or reprocessing (to minimize proliferation risk). No such reactors have ever been built.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**Yes / Likely**	See "Key Market-Related Issues" above.
Is the payback period for investment greater than 20 years?	**Maybe / Uncertain**	Motivations for an EDS will be other than commercial considerations.
Will the process benefit from existing facilities / infrastructure?	**No / Unlikely**	See "Key Market-Related Issues" above.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Yes / Likely**	See "Key Market-Related Issues" above.
Industry Structure		
Are significant changes to the industry required?	**Yes / Likely**	Motivations for an EDS will be other than commercial considerations.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Yes / Likely**	See "Key Market-Related Issues" above.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	The main "output" of reactors processes is electricity, for which there is a market.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Only one EG is expected to utilize this process.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Significant**	

Table D-2.21.15. Responses for Process RP-1, Reprocessing with RU/Pu Product.

Process: RP-1

Description Reprocessing with RU/Pu product

Key Market-Related Issues

Note that the market issues related to reprocessing are considered to be the same for all of the six reprocessing "processes" (RP-1 through RP-6) identified. The assessment for reprocessing is contained on this worksheet. RP-1 represents current types of technologies; there is some experience with Pu recycling. Areva operates a Pu reprocessing facility for France; in the US, only the goverment has done any reprocessing. The level of government interevention in RP-1 is considered to be less than the other RP processes. It is likely that large-scale facilities will be required (or lots of small-scale facilities), raising issues related to capital at risk, incentives, and market drivers. It is the assessment of the EST that utilities are not interested in reprocessing and will not invest in it without significant incentives or "outside" investment.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**Yes / Likely**	New commercial process - new step in the fuel cycle value chain, requiring new facilities and new capital at risk.
Is the payback period for investment greater than 20 years?	**Yes / Likely**	Given scale of facilities and potential need to build capacity in advance of need… expect payback periods to be relatively long (beyond 20 yr).
Will the process benefit from existing facilities / infrastructure?	**No / Unlikely**	There are not existing facilities or infrastructure related to reprocessing.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Yes / Likely**	Reprocessing introduces and extra step that needs to be integrated into an alreadycomplex system, introducing additional complexity, inventory management, storage issues.
Industry Structure		
Are significant changes to the industry required?	**Yes / Likely**	Very differnet from today's industry, with the introduction of an additional step (or more) into the value chain. Reprocess and recycle fuel fab can be seen as a new industry.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Yes / Likely**	Either single large scale facility or multiple small-scale facilities will be required.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**No / Unlikely**	No existing market for payment for a reccyle fuel. Market would need to be established. (what is the value to government, industry, society of spend fuel avoidance?)
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**Yes / Likely**	Waste fee of 1mill/kWh is a disincentive to any technology that reduces waste volumes without generating other commecial benefits to the utility.
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial	**Yes / Likely**	Several EGs include reprocessing
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Significant**	There are limited commercial motivations for reprocessing, and commercial players have indicated an interest in co-investing with the government under a pulic-private enterprise.

Table D-2.21.16. Responses for Process RP-2, Reprocessing with RU/TRU Product.

Process:	RP-2
Description	Reprocessing with RU/TRU product

Key Market-Related Issues

Note that the market issues related to reprocessing are considered to be the same for all of the six reprocessing "processes" (RP-1 through RP-6) identified. The assessment for reprocessing is contained on this worksheet. RP-1 represents current types of technologies; there is some experience with Pu recycling. Areva operates a Pu reprocessing facility for France; in the US, only the goverment has done any reprocessing. The level of government interevention in RP-1 is considered to be less than the other RP processes. It is likely that large-scale facilities will be required (or lots of small-scale facilities), raising issues related to capital at risk, incentives, and market drivers. It is the assessment of the EST that utilities are not interested in reprocessing and will not invest in it without significant incentives or "outside" investment.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	Yes / Likely	New commercial process - new step in the fuel cycle value chain, requiring new facilities and new capital at risk.
Is the payback period for investment greater than 20 years?	Yes / Likely	Given scale of facilities and potential need to build capacity in advance of need… expect payback periods to be relatively long (beyond 20 yr).
Will the process benefit from existing facilities / infrastructure?	No / Unlikely	There are not existing facilities or infrastructure related to reprocessing.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	Yes / Likely	Reprocessing introduces and extra step that needs to be integrated into an alreadycomplex system, introducing additional complexity, inventory management, storage issues.
Industry Structure		
Are significant changes to the industry required?	Yes / Likely	Very differnet from today's industry, with the introduction of an additional step (or more) into the value chain. Reprocess and recycle fuel fab can be seen as a new industry.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	Yes / Likely	Either single large scale facility or multiple small-scale facilities will be required.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	No / Unlikely	No existing market for payment for a recycle fuel. Market would need to be established (what is the value to government, industry, society of spend fuel avoidance?).
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	Yes / Likely	Waste fee of 1mill/kWh is a disincentive to any technology that reduces waste volumes without generating other commecial benefits to the utility.
Are there laws or regulations that are likely to encourage the development of this process?	No / Unlikely	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	Yes / Likely	Several EGs include reprocessing.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	Highly Significant	Likely government enterprise. There are no commercial motivations for reprocessing, and a general reluctance from the current commercial players.

Table D-2.21.17. Responses for Process RP-3, Reprocessing with U3/Th/TRU Products.

13 **Process:**	RP-3
Description	Reprocessing with U3/Th/TRU products

Key Market-Related Issues

Note that the market issues related to reprocessing are considered to be the same for all of the six reprocessing "processes" (RP-1 through RP-6) identified. The assessment for reprocessing is contained on this worksheet. RP-1 represents current types of technologies; there is some experience with Pu recycling. Areva operates a Pu reprocessing facility for France; in the US, only the goverment has done any reprocessing. The level of government interevention in RP-1 is considered to be less than the other RP processes. It is likely that large-scale facilities will be required (or lots of small-scale facilities), raising issues related to capital at risk, incentives, and market drivers. It is the assessment of the EST that utilities are not interested in reprocessing and will not invest in it without significant incentives or "outside" investment.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to	**Yes / Likely**	New commercial process - new step in the fuel cycle value chain, requiring new facilities and new capital at risk.
Is the payback period for investment greater than 20 years?	**Yes / Likely**	Given scale of facilities and potential need to build capacity in advance of need…expect payback periods to be relatively long (beyond 20 yr).
Will the process benefit from existing facilities / infrastructure?	**No / Unlikely**	There are not existing facilities or infrastructure related to reprocessing.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Yes / Likely**	Reprocessing introduces and extra step that needs to be integrated into an alreadycomplex system, introducing additional complexity, inventory management, storage issues.
Industry Structure		
Are significant changes to the industry required?	**Yes / Likely**	Very differnet from today's industry, with the introduction of an additional step (or more) into the value chain. Reprocess and recycle fuel fab can be seen as a new industry.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Yes / Likely**	Either single large scale facility or multiple small-scale facilities will be required.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**No / Unlikely**	No existing market for payment for a recycle fuel. Market would need to be established (what is the value to government, industry, society of spend fuel avoidance?).
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**Yes / Likely**	Waste fee of 1mill/kWh is a disincentive to any technology that reduces waste volumes without generating other commecial benefits to the utility.
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capability		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Several EGs include reprocessing.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Highly Significant**	Likely government enterprise. There are no commercial motivations for reprocessing, and a general reluctance from the current commercial players.

Table D-2.21.18. Responses for Process FF-3, Recycle Fuel Fabrication with RU/Pu.

Process:	FF-3
Description	Recycle fuel fabrication with RU/Pu

Key Market-Related Issues

This process is considered, from the market factors perspective, to be identical to FF-2 (fuel fabrication with thorium; uranium/thorium). The assessment for reprocessing is contained on the sheet for FF-2.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**Yes / Likely**	Depending on the thermal reactor design, there might be significant deviation from the current fuel fabrication approach.
Is the payback period for investment greater than 20 years?	**No / Unlikely**	Fuel fabrication is currenty conducted on a commercial basis, so fabrication with other materials is likely to enter into that same market, with an commensurate commercial project payback period.
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	It is likely that new facilities will resemble and benefit from existing facilities and infrastructure for fuel fabrication.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Maybe / Uncertain**	Fuel fabrication and reactor type are integrated/linked. Need for inventory management "starts" here.
Industry Structure		
Are significant changes to the industry required?	**No / Unlikely**	Buyers, sellers, and market mechanisms for fabricated fuels will not likely change with a move to thorium-based or advanced fuels.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Yes / Likely**	New fuel fabrication facilities will be required.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	See "Key Market-Related Issues" above
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**Maybe / Uncertain**	Uncertain since this process has not been introduced in the US.
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Investments in advanced fuel fabrication will likely apply to multiple EG's.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Limited**	Some incentives may be required to induce investment in the fabrication capacity needed to support new reactors. This investment needs to be made simultaneously with investment in generation. This intoduces financial risk as capacity investments will be required in advance of demonstrated demand.

Table D-2.21.19. Responses for Process FF-4, Recycle Fuel Fabrication with RU/TRU.

Process: FF-4

Description Recycle fuel fabrication with RU/TRU

Key Market-Related Issues

New fuel fabrication facilities will be required. The recycled fuel fabrication may be either centralized in one or a few larger plants, or distributed to each reactor site as in the IFR concept. In all likelihood, fuel fabrication will be co-located with fuel processing. Requires remote handling.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**Yes / Likely**	New, potentially large scale facilities required.
Is the payback period for investment greater than 20 years?	**Maybe / Uncertain**	
Will the process benefit from existing facilities / infrastructure?	**No / Unlikely**	Different from what is currently utilized in the US.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Yes / Likely**	Remoted handling required.
Industry Structure		
Are significant changes to the industry required?	**Yes / Likely**	
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Yes / Likely**	
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**No / Unlikely**	
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**Maybe / Uncertain**	
Are there laws or regulations that are likely to encourage the development of this process?	**Maybe / Uncertain**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Highly Significant**	

Table D-2.21.20. Responses for Process FF-5, Recycle Fuel Fabrication with U3/Th/TRU.

Process:	FF-5
Description	Recycle fuel fabrication with U3/Th/TRU

Key Market-Related Issues

New fuel fabrication facilities will be required. The recycled fuel fabrication may be either centralized in one or a few larger plants, or distributed to each reactor site as in the IFR concept. In all likelihood, fuel fabrication will be co-located with fuel processing.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**Yes / Likely**	New, potentially large scale facilities required.
Is the payback period for investment greater than 20 years?	**Yes / Likely**	
Will the process benefit from existing facilities / infrastructure?	**No / Unlikely**	Different from what is currently utilized in the US.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Yes / Likely**	Remoted handling required.
Industry Structure		
Are significant changes to the industry required?	**Yes / Likely**	
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Yes / Likely**	
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**No / Unlikely**	
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**Maybe / Uncertain**	
Are there laws or regulations that are likely to encourage the development of this process?	**Maybe / Uncertain**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**No / Unlikely**	
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Highly Significant**	

Table D-2.21.21. Responses for Process RX-1r, Thermal Critical Reactor with Recycle Fuel.

Process:	RX-1r
Description	Reactor with recycle fuel: Thermal-critical

Key Market-Related Issues

Note that the market issues related to Reactors with recycle fuel are considered identical to the market issues relate to the (same) Reactor type using "new" fuels. So the assessment for RX-1r is the same as that for RX-1, etc.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**No / Unlikely**	The process is similar to LWR's in operation today. Aging facilities will be replaced but singificant new investment will not be required.
Is the payback period for investment greater than 20 years?	**Not Applicable**	
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	Existing LWR technologies can be used for stages of the system.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**No / Unlikely**	Multi-stage systems will introduce greater complexity.
Industry Structure		
Are significant changes to the industry required?	**No / Unlikely**	Multi-stage systems will require changes in the industry.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**No / Unlikely**	Multi-stage systems will require new large scale facilities.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	The main "output" of reactors processes is electricity, for which there is a market.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Investments in this process will likely apply to multiple EG's.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Deminimus**	This will depend on the Evaluation Group. However, the extent of government intervention will be reflected in the Evaluation Groups that include reprocessing.

Table D-2.21.22. Responses for Process RX-2r, Thermal Critical Reactor with Advanced Recycle Fuels.

Process:	RX-2r
Description	Reactor with recycle fuel: Thermal-critical with advanced fuels

Key Market-Related Issues

Note that the market issues related to Reactors with recycle fuel are considered identical to the market issues relate to the (same) Reactor type using "new" fuels. So the assessment for RX-1r is the same as that for RX-1, etc.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**Yes / Likely**	See "Key Market-Related Issues" above
Is the payback period for investment greater than 20 years?	**Maybe / Uncertain**	For some EG, payback period will be less than 20yrs. For others it is not likely.
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Maybe / Uncertain**	May need to consider this on an EG level.
Industry Structure		
Are significant changes to the industry required?	**No / Unlikely**	
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**No / Unlikely**	Reactor size/scaling/penetration will be similar to that for the current fuel cycle.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Limited**	If fuels are available, commercial utilities would not need a lot of incentive or government investments to use those fuels (esp. where existing facilities and be used with slight modification); May need to consider differences on an EG level.

Table D-2.21.23. Responses for Process RX-3r, Fast Critical Reactor with Recycle Fuel.

Process: RX-3r
Description Reactor with recycle fuel: Fast-critical
Key Market-Related Issues

Note that the market issues related to Reactors with recycle fuel are considered identical to the market issues relate to the (same) Reactor type using "new" fuels. So the assessment for RX-1r is the same as that for RX-1, etc.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to	**Yes / Likely**	See "Key Market-Related Issues" above
Is the payback period for investment greater than 20 years?	**Maybe / Uncertain**	
Will the process benefit from existing facilities / infrastructure?	**Maybe / Uncertain**	
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Yes / Likely**	
Industry Structure		
Are significant changes to the industry required?	**Maybe / Uncertain**	
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Maybe / Uncertain**	Large scale facilities are expected but it is unclear whether facilities larger than those currently utilized will be required?
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	The main "output" of reactors processes is electricity, for which there is a market.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Only one EG is expected to utilize this process.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Significant**	

Table D-2.21.24. Responses for Process RX-4r, Sub-critical Reactor with Recycle Fuel.

Process: RX-4r

Description Reactor with recycle fuel: Sub-critical

Key Market-Related Issues

Note that the market issues related to Reactors with recycle fuel are considered identical to the market issues relate to the (same) Reactor type using "new" fuels. So the assessment for RX-1r is the same as that for RX-1, etc.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	**Yes / Likely**	See "Key Market-Related Issues" above.
Is the payback period for investment greater than 20 years?	**Maybe / Uncertain**	Motivations for an EDS will be other than commercial considerations.
Will the process benefit from existing facilities / infrastructure?	**No / Unlikely**	See "Key Market-Related Issues" above.
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Yes / Likely**	See "Key Market-Related Issues" above.
Industry Structure		
Are significant changes to the industry required?	**Yes / Likely**	Motivations for an EDS will be other than commercial considerations.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**Yes / Likely**	See "Key Market-Related Issues" above.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	The main "output" of reactors processes is electricity, for which there is a market.
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**No / Unlikely**	
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	Only one EG is expected to utilize this process.
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Significant**	

Table D-2.21.25. Responses for Process ST-1, Storage of Nuclear Materials.

Process: ST-1

Description Storage of nuclear materails

Key Market-Related Issues

Storage required at all stages of the fuel cycle system. (EG01-22, 24-40). Storage to varying degrees is required at all stages of the fuel cycle system. This investment requirement appears to apply to all valuation groups and would serve to mitigate concerns over linkages and integration. Transportation requirements will vary by evaluation groups. In some cases, it is likely that processing and fuel fabrication will be co-located. This could limit the market-related issues of evaluation groups that can benefit from co-location. Any system that closes the loop will require "inventory" type storage. This mitigates technical complexity but requires additional investments. Unclear whether the storage aspect would require government investment, although govt investment is likely to be required in the processes surrounding it. Storage is necessary for every step where there is material transfer. There is also a need for pre-disposal storage (and different fuel cycles may have different need for pre-disposal storage).

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to	**Yes / Likely**	
Is the payback period for investment greater than 20 years?	**No / Unlikely**	
Will the process benefit from existing facilities / infrastructure?	**Yes / Likely**	Current system has some storage capacity for new fuels (and some for used fuels).
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	**Not Applicable**	"inventory" storage mitigates the complexity and linkages of those systems of which it is a part.
Industry Structure		
Are significant changes to the industry required?	**Maybe / Uncertain**	There is storage today -- for fuel cycles that close the loop additional storage capability is likely to be required. It is possible, but not necessary, that a new "step" in the fuel cycle value chain would emerge to address the "insurance" storage needs; could instead be handled with an expansion of storage capacity of existing players.
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	**No / Unlikely**	Storage facilities can be built with "contingency" storage so that the full capacity does not have to be build out in advance.
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	**Yes / Likely**	
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	**Maybe / Uncertain**	
Are there laws or regulations that are likely to encourage the development of this process?	**No / Unlikely**	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	**Yes / Likely**	
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	**Limited**	

Table D-2.21.26. Responses for Process TR-1, Transport of Nuclear Materials.

Process:	TR-1
Description	Transport of nuclear materials

Key Market-Related Issues

If there is a process/facility within an evaluation group that is necessarily large (e.g. centralized reprocessing), there will be transportation between facilities. All EGs have transportation of spent fuel to a repository; that is ignored for this evaluation. The only other "big" transportation step would be transport to a centralized reprocessing. Different types of fuels / different spent fuels can be more or less difficult to transport (e.g., advanced fuels; MOX). However, this involves location and technology choices and cannot be addressed within the market considerations at this time.

FACTOR	ASSESSMENT	DESCRIPTION
Capital At Risk		
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	No / Unlikely	
Is the payback period for investment greater than 20 years?	Not Applicable	
Will the process benefit from existing facilities / infrastructure?	Yes / Likely	
Technical Complexity		
Is the process likely to be technifically complex and tightly integrated with other processes?	Yes / Likely	
Industry Structure		
Are significant changes to the industry required?	No / Unlikely	
Scaling / Penetration		
Does the plausible deployment scenario require new large scale facilities?	No / Unlikely	
Market Systems for Cost Recovery		
Are there likely to be market mechanisms in place to faciliate payment for the outputs?	Yes / Likely	
Market Distortions		
Are there laws or regulations that are likely to inhibit the development of this process?	Maybe / Uncertain	Some issues for different fuels (e.g., Hotter fuels must be transported in smaller packages), but those issues are relatively minor.
Are there laws or regulations that are likely to encourage the development of this process?	No / Unlikely	
Flexibility / Forward Capatibility		
Is investment in this process directly applicable to numerous other Evaluation Groups, or to other existing industrial processes?	Yes / Likely	
How Much Participation will be Required by the Federal Government?		
Highly Significant: The government will need to fully fund the required investments or mandate the use of the process through changes in law or regulations. **Significant:** The government will need to share the costs through direct investment or encourage the use of the process through changes in law or regulations. **Limited:** The government may need to induce investment through new financial or regulatory incentives. **Deminimus:** Routine / ordinary investment, incentives or actions by the Federal government is required.	Deminimus	

C. Assign Processes to Evaluation Groups

Each Evaluation Group was reviewed to identify applicable processes. This process mapping was utilized for several of the development and deployment metrics. Table D-2.21.27 depicts the mapping of all the processes to Evaluation Groups.

Table D-2.21.27. Process Mapping of Evaluation Groups.

Evaluation Group		Group ID	REPRESENTATIVE OPTION Reactor ([Startup]Driver; Blanket; Waste)	Fuel Material Supply		Uranium Enrichment		Fuel Fabrication from New Resources		Reactors (critical and sub-critical)				Reprocessing			Recycle Fuel Fabrication (shielded)			Recyle Reactors (critical and sub-critical)				Storage	Transport	Disposal			Total # of Processes for the EG
				FS-1	FS-2	UE-1	UE-2	FF-1	FF-2	RX-1	RX-2	RX-3	RX-4	RP-1	RP-2	RP-3	FF-3	FF-4	FF-5	RX-1r	RX-2r	RX-3r	RX-4r	ST-1	TR-1	DS-1	DS-2	DS-3	
EG01	OT1A	OT-C-T-U-Y	LWR(LEU; ; DF)	✓		✓		✓		✓														✓	✓	✓	✓		8
EG02	OT1B	OT-C-T-U-Y	HTGR(LEU;;DF)	✓		✓		✓			✓													✓	✓	✓	✓		8
EG03	OT01C	OT-C-T-U-N	HWR(NU;;DF)	✓				✓		✓														✓	✓		✓		6
EG04	OT02	OT-C-F-U-N	SFR ([LEU]TRU;DU;DF)	✓				✓				✓												✓	✓		✓		6
EG05	OT03	OT-C-T-UTh-Y	HTGR(LEU/Th;;DF)	✓	✓	✓			✓		✓													✓	✓	✓	✓		9
EG06	OT04	OT-C-T-Th-N	ADS([LEU];Th;DF)		✓				✓				✓											✓	✓		✓		6
EG07	OT05	OT-S-F-U-N	ADS(;NU;DF)	✓				✓					✓											✓	✓		✓		6
EG08	OT06	OT-S-F-Th-N	FFH(;Th;DF)	✓					✓				✓											✓	✓		✓		6
EG09	SL01	SL-C-F-U-TRU-N	SFR([LEU]TRU/RU;NU;DF-FP)	✓				✓							✓			✓				✓		✓	✓	✓	✓		9
EG10	SL02	SL-C-T-Th–U3-N	MSR([LEU]U3/Th;;Th-TRU-FP)		✓				✓							✓			✓		✓			✓	✓		✓		8
EG11	SL03	SL-C-F-Th-U3-N	SFR(LEU/U3/Th;Th;DF-FP)	✓	✓		✓		✓							✓			✓			✓		✓	✓		✓	✓	11
EG12	ML01	ML-C-T-U-Pu-N	HWR(NU;;U-MA-FP) →PWR(Pu/RU;;DF)	✓				✓		✓				✓			✓			✓				✓	✓		✓	✓	10
EG13	ML02	ML-C-T-U-Pu-Y	PWR(LEU;;U-MA-FP) →PWR(Pu/RU;;DF)	✓		✓		✓		✓				✓			✓			✓				✓	✓	✓	✓	✓	12
EG14	ML03	ML-C-T/F-U-Pu-N	SFR([LEU]Pu/RU;NU;MA-FP) →PWR(Pu /RU;;DF)	✓				✓						✓			✓			✓		✓		✓	✓		✓	✓	10
EG15	ML04	ML-C-T/F-U-Pu-Y	PWR(LEU;;U-MA-FP) →SFR(Pu/RU;RU;DF)	✓		✓		✓		✓				✓			✓					✓		✓	✓	✓	✓	✓	12
EG16	ML05	ML-C/S-T/F-U-Pu-Y	PWR(LEU;;U-MA-FP) →ADS(Pu/IMF;;DF)	✓		✓		✓		✓				✓			✓						✓	✓	✓	✓	✓	✓	12
EG17	ML06	ML-C-T-UTh-Pu-Y	PWR(LEU;;U-MA-FP) → PWR(Pu/Th;;DF)	✓	✓	✓		✓		✓				✓					✓	✓				✓	✓	✓	✓	✓	13
EG18	ML07	ML-C-T-UTh-U3-Y	PWR(LEU/Th;;Th-U-TRU-FP) → PWR(U3/Th;;Th-TRU-FP-DF)	✓	✓	✓			✓	✓						✓			✓	✓				✓	✓	✓	✓	✓	13
EG19	SC01	SC-C-T-U-Pu-N	HWR([NU]Pu/NU;;U-MA-FP)	✓										✓			✓			✓				✓	✓		✓	✓	8
EG20	SC02	SC-C-T-U-TRU-N	HWR([NU]TRU/NU;;U-FP)	✓											✓			✓		✓				✓	✓		✓	✓	8
EG21	SC03	SC-C-T-U-Pu-Y	PWR(LEU+Pu/RU;;U-MA-FP)	✓		✓		✓						✓			✓			✓				✓	✓	✓	✓	✓	11
EG22	SC04	SC-C-T-U-TRU-Y	PWR(LEU+TRU/RU;;U-FP)	✓		✓		✓							✓			✓		✓				✓	✓	✓	✓	✓	11
EG23	SC05	SC-C-F-U-Pu-N	SFR([LEU]Pu/RU;NU;MA-FP)	✓										✓			✓					✓		✓	✓		✓	✓	8
EG24	SC06	SC-C-F-U-TRU-N	SFR([LEU]TRU/RU;NU;FP)	✓											✓			✓				✓		✓	✓		✓	✓	8
EG25	SC07	SC-C-T-UTh-U3-Y	PWR(LEU;U3/Th;U-Th-Pu-MA-FP)	✓	✓	✓		✓								✓			✓			✓		✓	✓		✓	✓	11
EG26	SC08	SC-C-T-Th-U3-N	MSR([LEU]U3/Th;;TRU-FP)		✓				✓							✓			✓		✓			✓	✓		✓	✓	9
EG27	SC09	SC-C-F-UTh-U3-Y	SFR(LEU/U3/Th;;U-Pu-MA-FP)	✓	✓		✓		✓							✓			✓			✓		✓	✓		✓	✓	11
EG28	SC10	SC-C-F-Th-U3-N	SFR([LEU]U3/Th;;FP)	✓	✓				✓							✓			✓			✓		✓	✓		✓	✓	10
EG29	MC01	MC-C-T/F-U-Pu-N	SFR([LEU]Pu/RU;NU;MA-FP) →PWR(Pu/RU;;U-MA-FP)	✓				✓							✓		✓			✓		✓		✓	✓			✓	9
EG30	MC02	MC-C-T/F-U-TRU-N	SFR([LEU]TRU/RU;NU;FP) →PWR(Pu/RU;;FP)	✓				✓							✓			✓		✓		✓		✓	✓			✓	9
EG31	MC03	MC-C-T/F-U-Pu-Y	PWR(LEU;;U-MA-FP) →SFR(Pu/RU;NU;U-MA-FP)	✓		✓		✓		✓					✓		✓					✓		✓	✓	✓		✓	11
EG32	MC04	MC-C-T/F-U-TRU-Y	PWR(LEU;;U-FP) →SFR(TRU/RU;;FP)	✓		✓		✓		✓					✓			✓				✓		✓	✓	✓		✓	11
EG33	MC05	MC-C/S-T/F-U-Pu-N	ADS(;NU;MA-FP) →PWR(Pu/RU;;MA-FP)	✓				✓					✓		✓		✓			✓				✓	✓			✓	9
EG34	MC06	MC-C/S-T/F-U-TRU-N	ADS(;NU;FP) →PWR(TRU/RU;;FP)	✓				✓					✓			✓		✓		✓				✓	✓			✓	9
EG35	MC07	MC-C/S-T/F-U-Pu-Y	PWR(LEU;;U-MA-FP) →ADS(Pu/IMF;;U-MA-FP)	✓		✓		✓		✓				✓			✓						✓	✓	✓	✓		✓	11
EG36	MC08	MC-C/S-T/F-U-TRU-Y	PWR(LEU+Pu/RU;;U-FP) →ADS(MA/IMF;;FP)	✓		✓		✓							✓			✓		✓			✓	✓	✓	✓		✓	11
EG37	MC09	MC-C-T/F-UTh-U3-Y	PWR(LEU;;U-FP) → SFR(TRU/RU; Th; FP) → PWR(U3/RU;;FP)	✓	✓	✓			✓	✓						✓		✓	✓	✓		✓		✓	✓	✓		✓	14
EG38	MC10	MC-C-T/F-Th-U3-N	SFR([LEU]U3/Th; Th; FP) →PWR(U3/Th;;FP)		✓				✓							✓			✓	✓		✓		✓	✓			✓	9
EG39	MC11	MC-C/S-T/F-UTh-U3-Y	PWR(LEU;Th;U-Th-FP) → PWR(U3/Th;;Th-FP) → ADS(TRU/IMF;;U-Th-FP)	✓	✓	✓			✓	✓						✓		✓	✓	✓			✓	✓	✓	✓		✓	14
EG40	MC12	MC-C/S-T/F-Th-U3-N	ADS(Th;;Th-FP) → PWR(U3/Th;;Th-Pu-MA-FP)	✓	✓				✓				✓			✓			✓	✓				✓	✓		✓		10
# EGs using the process				36	14	17	2	23	13	13	2	1	6	10	10	12	12	10	12	18	2	15	4	40	40	17	29	29	

D. Development of Metric Data

As presented in Appendix C-7.8, three bins were identified for market drivers as shown in Table 2.21.28.

Table D-2.21.28. Market Incentives and Drivers "Bins".

Market Driver "Bins"	
A	Markets and market mechanisms exist that support private investment for most of the fuel cycle processes/facilities needed for the fuel cycle option and Federal government intervention in the form of direct investment or mandates will not be required for most of the fuel cycle processes.
B	Markets and market mechanisms exist that support private investment for some of the fuel cycle processes/facilities needed for the fuel cycle option and significant or sustained Federal government intervention in the form of direct investment or mandates will not be required to establish market drivers.
C	Markets and market mechanisms are weak or exhibit distortions, requiring significant and sustained Federal government intervention in the form of direct investment or changes in law in order to establish market drivers.

To assign Evaluation Groups to the market incentive bins, the results for processes relevant to the Evaluation Group were examined to determine how the market incentives affected the Evaluation Group as a whole. Table D-2.24.29 provides example results for EG01, the Basis for Comparison.

Table D-2.21.29. Market Incentives and Drivers EG01.

Market Incentives and Drivers - EG01	**Fuel Material Supply** **FS-1**	**Enrichment** **UE-1**	**Fuel Fabrication** **FF-1**	**Reactors** **RX-1**	**Storage** **ST-1**	**Transport** **TR-1**
1. Industry structure: Are significant changes to the industry required?	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Maybe / Uncertain	No / Unlikely
2. Market systems for cost recovery: Are there likely to be market mechanisms in place to facilitate payment for the outputs?	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely
3. Market distortions: Are there laws or regulations that are likely to inhibit the development of this process?	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Maybe / Uncertain	Maybe / Uncertain
4. Market distortions: Are there laws or regulations that are likely to encourage the development of this process?	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely
5. How Much Participation will be Required by the Federal Government?	Deminimus	Deminimus	Deminimus	Deminimus	Limited	Deminimus

For comparison purposes, the results for another Evaluation Group, EG40, is provided in Table D-2.21.30.

Table D-2.21.30. Market Incentives and Drivers for EG40.

Market Incentives and Drivers – EG01	Fuel Material Supply FS-1	Fuel Material Supply FS-2	Fuel Fabrication FF-2	Reactors RX-4	Reprocess RP-3	Recycle Fuel Fab FF-5	Recycle Reactors RX-1r	Storage ST-1	Transport TR-1
1. Industry structure: Are significant changes to the industry required?	No / Unlikely	Maybe / Uncertain	No / Unlikely	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely	Maybe / Uncertain	No / Unlikely
2. Market systems for cost recovery: Are there likely to be market mechanisms in place to facilitate payment for the outputs?	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely	No / Unlikely	Yes / Likely	Yes / Likely	Yes / Likely
3. Market distortions: Are there laws or regulations that are likely to inhibit the development of this process?	No / Unlikely	No / Unlikely	Maybe / Uncertain	No / Unlikely	Yes / Likely	Maybe / Uncertain	No / Unlikely	Maybe / Uncertain	Maybe / Uncertain
4. Market distortions: Are there laws or regulations that are likely to encourage the development of this process?	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Maybe / Uncertain	No / Unlikely	No / Unlikely	No / Unlikely
5. How Much Participation will be Required by the Federal Government?	Deminimus	Deminimus	Limited	Significant	Highly Significant	Highly Significant	Deminimus	Limited	Deminimus

In order to provide meaningful differentiation among Evaluation Groups, rules of thumb were developed for assigning an Evaluation Group to a bin as shown in Table D-2.21.31.

Table D-2.21.31. Rules of Thumb for Assigning an Evaluation Group to a Bin – Market Incentives and Drivers.

Condition	Bin
The Evaluation Group (EG) includes a process that requires “Highly Significant” participation from the Federal Government.	**C**
The EG includes only processes that require “Limited” or “Deminimus” participation from the Federal Government AND across all processes included, there are more positive indicators than negative indicators on all other market incentives questions.	**A**
Neither of the two conditions above holds.	**B**

For capital at risk, five bins were identified as listed in Table D-2.21.32.

Table D-2.21.32. Capital At Risk “Bins”.

Capital at Risk “Bins”	
A	The fuel cycle option exhibits promise with respect to the capital investment required and benefits significantly from incentives related to capital at risk.
B	The fuel cycle option exhibits promise with respect to the capital investment required. Although disincentives exist, the fuel cycle option, on balance, benefits from incentives related to capital at risk.

C	The fuel cycle option is neutral with respect to the capital investment required, exhibiting off-setting incentives and disincentives.
D	The fuel cycle option exhibits challenges with respect to the capital investment required. While incentives exist, the fuel cycle option, on balance, is weakened from disincentives related to capital at risk.
E	The fuel cycle option exhibits challenges with respect to the capital investment required and is weakened significantly from disincentives related to capital at risk.

To assign Evaluation Groups to the capital at risk bins, the results for processes relevant to the Evaluation Group were examined to determine how capital at risk considerations affected the Evaluation Group as a whole. Table D-2.21.33 provides example results for EG01, the Basis for Comparison.

Table D-2.21.33. Capital at Risk EG01.

	Fuel Material Supply	**Enrichment**	**Fuel Fabrication**	**Reactors**	**Storage**	**Transport**
Capital at Risk - EG01	**FS-1**	**UE-1**	**FF-1**	**RX-1**	**ST-1**	**TR-1**
1. Capital Investment: Will the investment of substantial new capital (beyond the cost of replacing existing / aging facilities) be required to implement this process?	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	Yes / Likely	No / Unlikely
2. Payback Period: Is the payback period for investment greater than 20 years?	NA	NA	NA	Maybe / Uncertain	Maybe / Uncertain	NA
3. Scaling/Penetration: Does the plausible deployment scenario require new large scale facilities or numerous small-scale facilities?	No / Unlikely	Maybe / Uncertain	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely
4. Will the process benefit from existing facilities / infrastructure?	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely
5. Technical Complexity: Is the process likely to be technically complex and tightly integrated with other processes?	No / Unlikely	No / Unlikely	No / Unlikely	No / Unlikely	NA	Yes / Likely
6. Flexibility / Forward Compatibility: Is investment in this process directly applicable to numerous other Evaluation Groups, or to another existing industrial process?	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely

For comparison purposes, the results for another Evaluation Group, EG40, is provided in Table D-2.21.34. The answers to the six questions were highly correlated; processes that required substantial new capital tended to score "poorly" on most of the other questions as well.

Table D-2.21.34. Capital at Risk EG40.

	Fuel Material Supply		Fuel Fabri-cation	Reactors	Repro-cessing	Recycle Fuel Fabri-cation	Recycle Reactors	Storage	Tran-sport
Capital at Risk	**FS-1**	**FS-2**	**FF-2**	**RX-4**	**RP-3**	**FF-5**	**RX-1r**	**ST-1**	**TR-1**
Will the investment of substantial new capital (beyond the cost of replacing existing/aging facilities) be required to implement this process?	No / Unlikely	No / Unlikely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely	Yes / Likely	No / Unlikely
Scaling / penetration: Does the plausible deployment scenario require new large scale facilities?	No / Unlikely	No / Unlikely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely	No / Unlikely	No / Unlikely
Will the process benefit from existing facilities / infrastructure?	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely	No / Unlikely	No / Unlikely	Yes / Likely	Yes / Likely	Yes / Likely
Is the process likely to be technically complex and tightly integrated with other processes?	No / Unlikely	No / Unlikely	Maybe / Uncertain	Yes / Likely	Yes / Likely	Yes / Likely	No / Unlikely	Not Applicable	Yes / Likely
Flexibility / forward compatibility: Is investment in this process directly applicable to numerous other Evaluation Group, or to another existing industrial process?	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely	Yes / Likely

The Market Metric Working Group's examination of the five questions relative to each process highlighted that the investment of substantial new capital represented an important differentiating factor. Accordingly, the rules of thumb for Capital At Risk are given in Table D-2.21.35.

Table D-2.21.35. Capital At Risk - Rules of Thumb for Assigning an Evaluation Group to a Bin.

Condition	Bin
The EG includes two or more processes where substantial new capital and large scale facilities will be required. In practice, this includes any EG with reprocessing and anything other than a thermal-critical reactor.	**E**
The EG includes a reactor process requiring substantial new capital, but does not include reprocessing.	**D**
The EG includes reprocessing but does *not* include a reactor process requiring substantial new capital.	**C**
None of the three conditions above holds.	**B**

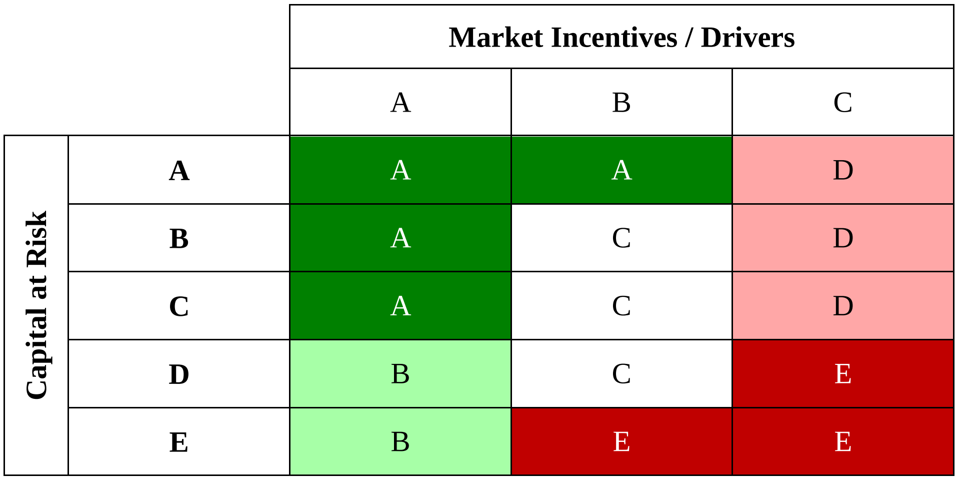
Notably, the rules of thumb did not support the assignment of an Evaluation Group into the A bin. This reflects the capital intensive nature of nuclear energy systems. Based on the analyses of fuel cycle processes and the aggregation of Evaluation Group information, the application of the rules of thumb for market incentives and drivers and capital at risk resulted in metric data for the two Market Metric factors. As described in Appendix C.7.8, the Market Metric bins are described in Table D-2.24.36 below.

Table D-2.21.36. Final Market Incentives and Drivers and/or Barriers Metric Result.

Final Market Metric Result	
A	Markets and market mechanisms exist that support private investment for most of the fuel cycle processes/facilities needed for the fuel cycle option, and Federal government intervention in the form of direct investment or mandates will not be required for most of the fuel cycle processes. In addition, the fuel cycle option exhibits promise with respect to the magnitude of capital investment required and payback prospects; on balance the fuel cycle option benefits from incentives related to capital at risk.
B	Markets and market mechanisms exist that support private investment for most of the fuel cycle processes/facilities needed for the fuel cycle option and Federal government intervention in the form of direct investment or mandates will not be required for most of the fuel cycle processes. However, the fuel cycle option exhibits challenges with respect to the magnitude of capital required and payback prospects, and on balance the fuel cycle option is weakened by disincentives related to capital at risk.
C	Markets and market mechanisms exist that support private investment for some of the fuel cycle processes/facilities needed for the fuel cycle option and, while some Federal government intervention in the form of direct investment, mandates or incentives may be necessary, significant and sustained Federal government intervention will *not* be required to promote investment.
D	Markets and market mechanisms are weak or exhibit distortions, requiring Federal government intervention in the form of direct investment or changes in law in order to establish and sustain market drivers. However, the fuel cycle option exhibits promise with respect to the magnitude of capital required and payback prospects, and benefits from incentives related to capital at risk.
E	Markets and market mechanisms are weak or exhibit distortions, requiring Federal government intervention in the form of direct investment or changes in law in order to establish and sustain market drivers. In addition, the fuel cycle option exhibits challenges with respect to the magnitude of capital required and payback prospects.

As discussed in Appendix C-7.8, market incentives and drivers were more influential than capital at risk consideration in determining the final market metric result. The matrix in Table D-2.21.37 illustrates the relationship of the factors to the final Market Incentives and/or Barriers metric result.

Table D-2.21.37. Relationship of Capital at Risk and Market Incentives/Drivers Bins to the Market Incentives and/or Barriers Metric Bins.



		Market Incentives / Drivers		
		A	B	C
Capital at Risk	**A**	A	A	D
	B	A	C	D
	C	A	C	D
	D	B	C	E
	E	B	E	E

The results of the analysis of each Evaluation Group for the market incentives and drivers and capital at risk factors are presented in Table D-2.21.38.

Table D-2.21.38. Results of Analysis of Each Evaluation Group.

Evaluation Group	Market Incentives "Score"	Capital at Risk "Score"	Final Market Metric Data
EG01	A	B	A
EG02	A	D	B
EG03	A	B	A
EG04	B	D	C
EG05	A	D	B
EG06	B	D	C
EG07	B	D	C
EG08	B	D	C
EG09	C	E	E
EG10	C	E	E
EG11	C	E	E
EG12	B	C	C
EG13	B	C	C
EG14	B	E	E
EG15	B	E	E
EG16	B	E	E
EG17	C	C	D
EG18	C	C	D
EG19	B	C	C
EG20	C	C	D
EG21	B	C	C
EG22	C	C	D
EG23	B	E	E
EG24	C	E	E
EG25	C	E	E
EG26	C	E	E
EG27	C	E	E
EG28	C	E	E
EG29	C	E	E
EG30	C	E	E
EG31	C	E	E
EG32	C	E	E
EG33	C	E	E
EG34	C	E	E
EG35	C	E	E
EG36	C	E	E
EG37	C	E	E
EG38	C	E	E
EG39	C	E	E
EG40	C	E	E

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.21.1 (using the data from Table 2.21.37 and the matrix from Table 2.21.38) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

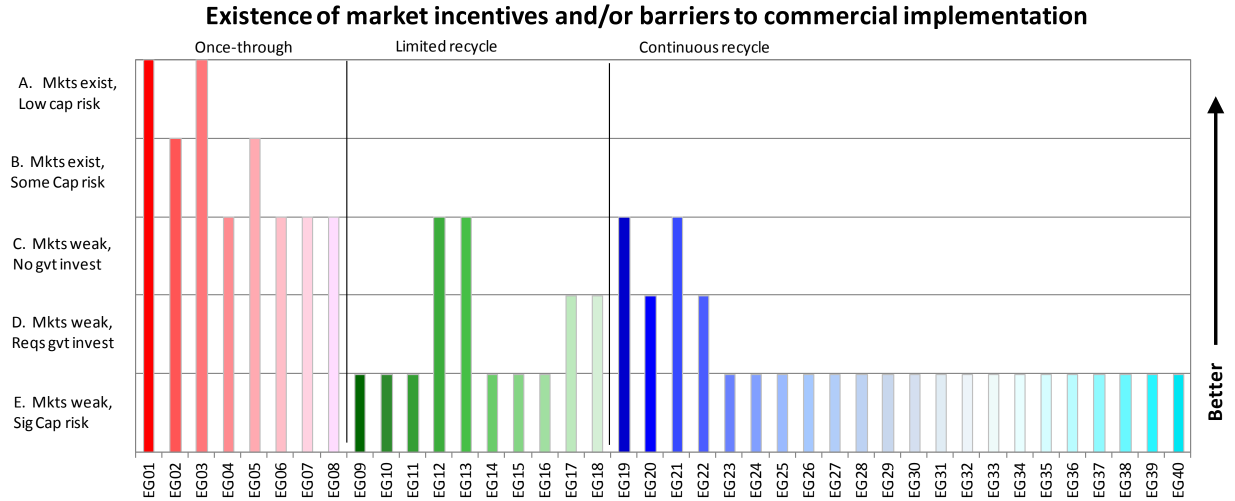


Figure D-2.21.1. Metric Data for the Existence of Market Incentives and/or Barriers to Commercial Implementation of Fuel Cycle Processes for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Metric Observations

The Existence of Market Incentives and/or Barriers to Commercial Implementation of Fuel Cycle Processes is a metric for Institutional Issues, one of the "challenge" criteria as described in Appendix A. As a consequence, this is a metric for which promising Evaluation Groups were not considered since all fuel cycle options will face challenges in achieving market incentives comparable to that for the Basis of Comparison.

The EST agreed that commercial considerations represent an institutional issue that can be factored in the evaluation of fuel cycle options. The Market Metric Working Group found that significant uncertainty accompanies the consideration of capital at risk and market drivers. However, the process of thinking through commercial issues provided a number of insights. These included the following:

- All fuel cycle options require a repository for disposal. Therefore, consideration of disposal did not represent a differentiating input to the market metric results.
- While time to payback represents an important consideration in the evaluation of investment options, all fuel cycle options will exhibit long payback periods. Meaningful differentiation among all processes with respect to payback could not be determined at this time.
- Numerous investments in fuel cycle processes were applicable across Evaluation Groups, suggesting that R&D investment will often not be exclusive to a single Evaluation Group.

The outputs of the analysis reflect the fact that Evaluation Groups that utilize existing processes and do not require the government to “make the market” performed well under the analytical framework. Specifically, EG01, the Basis of Comparison, is in bin A because it exists today. Accordingly, “market drivers” are present and challenges related to capital investment have been addressed. As Evaluation Groups involving additional new capital and/or introduced a requirement for new market drivers, they become less promising. In particular, Evaluation Groups with existing reactor technologies with high burn-up (EG02 or EG05) and Evaluation Groups with limited recycle exhibit promise. Other EGs exhibiting promise were those which, scored in Bin C, including EG04, EG06, EG07, EG08, EG12, EG13, EG19, EG21.

D-2.22 Levelized Cost at Equilibrium (LCAE)

Calculation of Metric Information

The Levelized Cost at Equilibrium (LCAE) was calculated for the Analysis Examples of the 40 Evaluation Groups to provide insight into the relative cost of producing electricity from an alternative fuel cycle. Such estimates are always subject to very high uncertainty, both in the cost estimates for each part of the fuel cycle and in the likely statistical distribution associated with such costs. In addition, cost uncertainties can be correlated based on commonalities between various parts of the fuel cycle, such as the use of steel and concrete for facilities. However, given the highly uncertain nature of the cost estimate, it was assumed for these analyses that cost uncertainties are uncorrelated. As discussed in Appendix C-9, the EST is well aware of these issues, and as a result used the LCAE only as an approximate guide to the relative changes in electricity production costs that may occur among fuel cycles. This information is provided for all Evaluation Groups, including the potentially promising options, as additional input to the DOE decision-making process.

The methodology for calculating LCAE is a statistical approach that uses a detailed model of a fuel cycle, as discussed in Appendix C-9, with Monte-Carlo sampling of the uncertainty distributions for each input parameter to arrive at the LCAE cost distribution for each Analysis Example. The calculated results for LCAE for each of the Analysis Examples are listed in Table D-2.22.1.

Table D-2.22.1. Summary Table for the Mean and Standard Deviation of the LCAE ($/MWh) of the 40 Evaluation Groups with a 5% Discount Rate.

Evaluation Group	**Analysis Example (as described in Appendix B-5)**	**LCAE ($/MWh)**	
		Mean	**2 x Std. Deviation**
EG01	Commercial PWR UOX once through	49.4	11.1
EG02	HTGR (graphite-moderated, He-cooled) with LEU fuel	67.6	19
EG03	Once Through Heavy Water Reactor with Natural Uranium	57.4	11.5
EG04	Breed and Burn SFR without separation	44.3	15.2
EG05	High-Conversion HTGR (graphite-moderated, He-cooled) with LEU and Th fuel	70	19.9
EG06	ADS(Th) to DF	115.1	33.5
EG07	ADS(NU) to DF	827.6	521.7
EG08	Subcritical Thorium Blanket Driven by an ICF Neutron Source	95.1	24.3
EG09	SFR Breed and Burn with Fuel Reconditioning	52.1	15.5
EG10	MSR-Th with limited recycle	86.7	28.4
EG11	Thorium Breed and Burn with LEU Support in SFR with Partial Separation	59.3	15.3
EG12	Recover Pu from HWR(NU) and limited recycle in PWR	66.1	9
EG13	Recover Pu from PWR and limited recycle in PWR (PWR-UOX to PWR-MOX)	53.6	11.1
EG14	SFR(Pu/U) to PWR(Pu/U) for limited recycling	52.4	11.5
EG15	Recover Pu from PWR and Recycle in SFR	52.2	10.2
EG16	Recover Pu from PWR and burn in ADS	85.1	31.8
EG17	Recover Pu from PWR and limited recycle in PWR with Thorium	52.6	11.1
EG18	Recover U3 from PWR and limited recycle in PWR	61.6	13.6
EG19	Continuous Pu recycle in HWR	128.6	33.2
EG20	Continuous TRU recycle in HWR	159.9	53.5
EG21	Continuous Pu recycle in PWR (CORAIL-Pu)	56.5	11.2
EG22	Continuous TRU recycle in PWR (CORAIL-TRU)	57.8	11.3
EG23	Continuous Pu Recycle in SFR	51.9	15.4
EG24	Continuous TRU recycle in SFR	55.5	15.8
EG25	U-233 Recycle in PWR with LEU Support	83.8	16.1
EG26	U-233 recycle in MSR	86.7	28.4
EG27	U-233 Recycle in SFR with LEU Support	72.3	16.7

EG28	Thorium fueled SFR for continuous recycling	77.2	19.2
EG29	Breed Pu in SFR and use extra Pu in PWR	53.7	10.7
EG30	Breed TRU in SFR and use extra Pu in PWR	53.1	13.6
EG31	Burn recovered Pu from PWR in SFR	51.2	9
EG32	Burn recovered TRU from PWR in SFR (GNEP scenario)	52.2	9.1
EG33	Breed Pu in ADS and use extra Pu in PWR	198.6	81.6
EG34	Breed TRU in ADS and use extra TRU in PWR	185.5	71.9
EG35	Burn recovered Pu from PWR in ADS	106.8	46.5
EG36	Recycle Pu in PWR and burn MA in ADS	65.9	12.2
EG37	PWR UOX, recycle TRU/breed U-233 in SFR, recycle U-233 in PWR	56.5	9.9
EG38	Recycle U-233 in SFR and PWR	92.3	21.7
EG39	PWR UOX and Th, recycle U-233 in PWRs, burn TRU in ADS	87.4	19.1
EG40	Breed U3 in ADS and recycle it in PWR	186.1	77.1

In addition to the caveats about the use of the mean value of LCAE, caution is advised concerning the information on standard deviation given that all input parameter uncertainty distributions were assumed to be independent (of necessity due to the limitation in knowledge about the input parameter data and correlation among input parameters) which can result in smaller standard deviations.

Fuel Cycle Contributions to Levelized Cost At Equilibrium

The analysis presented here focuses on identifying the major drivers and key contributors to the LCAE for each Evaluation Group. Figure D-2.22.1 shows, for each of the analysis examples for the 40 Evaluation Groups, a breakdown of the LCAE by major cost component using the expected value of each cost contributor. The uncertainty ranges associated with each of these values are not shown in Figure D-2.22.1. For the sake of simplicity and clarity, only the values with a 5% discount rate are presented in this section. For the calculations represented below, it is was assumed that the analysis examples for EG02 and EG05 feature a PWR instead of an HTGR, leading to lower costs than are shown in Table D-2.22.1. This was done in order to avoid an artificial cost differential from the selection of a different reactor technology for the thermal reactor in these fuel cycles since they are very similar to the current U.S. fuel cycle.

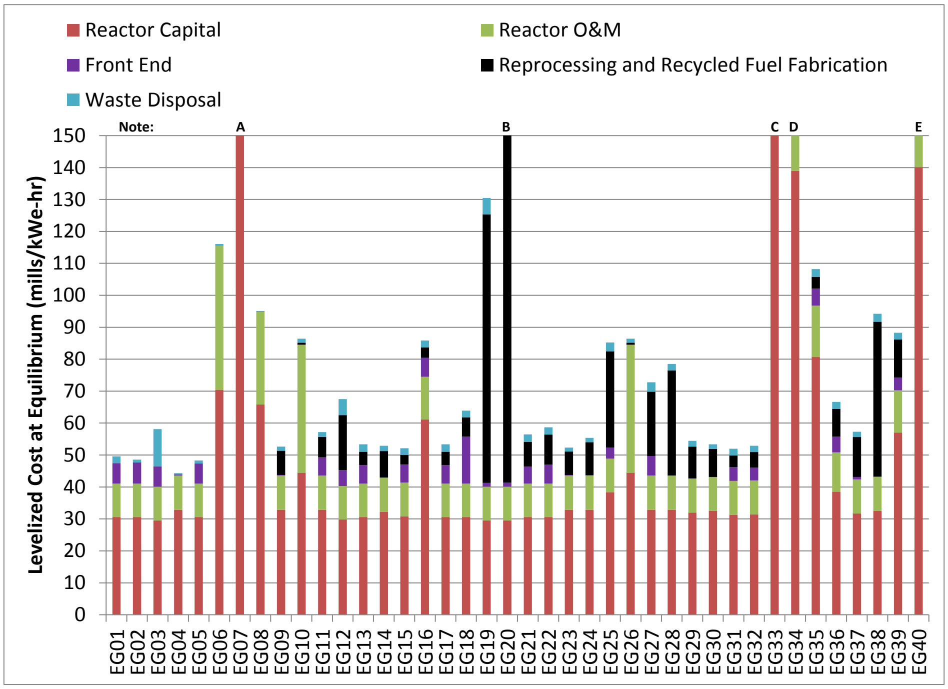


Figure D-2.22.1. Contributions to the LCAE for the Analysis Example of Each Evaluation Group and the Analysis Example of EG01.

(Notes for off-the-chart bars: A – EG07: Reactor Capital 780, Reactor O&M 55, Front End 1.9, Fuel Recycle 0, and Waste Disposal 2.2; B – EG20: Reactor Capital 30, Reactor O&M 11, Front End 1.2, Fuel Recycle 110, and Waste Disposal 5.2; C – EG33: Reactor Capital 150, Reactor O&M 35, Front End 0.4, Fuel Recycle 10, and Waste Disposal 1.8; D – EG34: Reactor Capital 139, Reactor O&M 35, Front End 0.4, Fuel Recycle 12, and Waste Disposal 1.5; and E – EG40:Reactor Capital 140, Reactor O&M 27, Front End 0.2, Fuel Recycle 15, and Waste Disposal 7.3)

The LCAE for Evaluation Groups with externally driven systems was generally substantially higher if an ADS was used as an external neutron source as compared to an FFH, both because (1) the ADS is a net user of electricity, while the FFH is a producer, and (2) because the cost data available thus far suggest that the capital cost of large ADS (with beam power of the order of hundreds of MW) would be substantially larger than similarly sized fusion-powered neutron source. The reader is cautioned, though, that because of low technological maturity level of these concepts, cost estimates have very large uncertainties. In the results presented here, most of the externally driven Evaluation Groups have been evaluated with analysis examples featuring an ADS, with the exception of EG06 and EG08, where the externally supplied neutrons are supplied by a fusion source. Generally the result of using ADS to drive fission blankets that supply a large fraction of the system electricity is an LCAE that far exceeds that of otherwise similar critical systems, as can be seen in Figure D-2.22.1.

The cost contributions to the LCAE, about 30 in total as discussed in Appendix C-9 have been rolled up into 5 groups for the bar chart of Figure D-2.22.1.

The first group, “Reactor Capital”, is the largest contributor for almost all of the Evaluation Groups. Reactor Capital includes charges for (1) recovery for the overnight construction cost of all the reactors in the system, (2) interest during construction, and (3) an adequate return on the capital invested.

The second group, “Reactor O&M”, is the second largest contributor for most Evaluation Groups. This group includes the fixed and variable operation and maintenance costs associated with the reactors, mostly manpower, but also non-fuel consumables, overhead, handling and disposal of LLW generated at the reactor, payment to decontamination and decommissioning (D&D) funds, and insurance.

The third group, “Front End”, includes the cost contribution associated with newly-mined fuel: natural uranium and thorium, conversion, and fabrication of fuels that contain only these materials, and uranium enrichment if required. Each Evaluation Group has at least some charges for newly-mined material procurement and fabrication, since no legacy material is assumed to exist for the equilibrium analyses that are the subject of this study. However, the relative importance of the Front End cost varies significantly by Evaluation Group, with Evaluation Groups featuring large uranium or thorium utilization through recycling or other means (i.e. breed and burn) requiring small expenditures for the supply of these materials. Fuel fabrication costs for newly-mined materials tend to be low since, because of the absence of strongly radioactive and/or radiotoxic recycled products, no special handling is required (e.g. glove box or remote fabrication).

The fourth group, “Reprocessing and Recycled Fuel Fabrication”, includes the cost contributions associated with the recycle of irradiated materials: separation and fabrication costs of fuels containing recycled materials (but no costs of natural uranium or thorium used as makeup, which are included in the “Front End” group). Evaluation Groups that do not include recycling have no cost contribution from this group. On the other hand, Reprocessing and Recycled Fuel Fabrication cost contributions can be very high, and even dominant, for Evaluation Groups (such as EG19 and EG20) that require very frequent recycling of large fuel masses per unit of energy generated.

The fifth group, “Waste Disposal”, is the cost of preparation, shipment, and disposal of SNF, HLW, DU, and RU waste. It does not include LLW, which is included in the unit costs of each component which generates LLW for fuel cycle facilities, and in the O&M costs for the reactors. Each Evaluation Group has a “Waste Disposal” cost contribution, since final disposal is always required. As discussed in Appendix C-9, the cost of waste disposal in the LCAE is not based on the current 1 mil per kWhr fee specified by the Nuclear Waste Policy Act of 1982. Instead, a disposal cost for geologic disposal based on the amount of waste is used. Based on the cost studies performed thus far, the “Waste Disposal” contribution is usually relatively large only for the Evaluation Groups that feature very low average discharge burnup, therefore producing a large mass of SNF for the once-through option, or large process losses due to frequent recycles. However, it is stressed that no geologic repository has been finalized and operated thus far on a commercial basis, in any part of the world. For this reason, the disposal costs are only based on cost studies for LWR SNF and HLW, and are highly uncertain for other spent nuclear fuel forms. However, the cost of geologic waste disposal is likely to remain a small levelized cost component (<5% of total LCAE) for nearly all fuel cycle options.

Determination of Metric Data

This basic method of calculating the difference in levelized (including discounting) quantity of items between fuel cycles and then applying the range of unit costs from The Advanced Fuel Cycle Cost Basis Report AFCCBR provides a very straightforward approach to comparing the potential differences between fuel cycle costs. This method is also consistent with the meaning of the unit costs provided in the AFCCBR. While a distribution is provided for the unit costs, it is based on a range with an upside (low unit cost value in the range) and a downside (high unit cost value in the range). Most are then assumed to have a simple triangular probability density function distribution which requires the identification of a mode (most probable) or mean value while a few assume a uniform distribution between the upside and downside values of the cost range and therefore by definition the mean becomes the midpoint. This suggests treating this data as a range more than an actual probability distribution seems very consistent with the fidelity of the data.

All cost values are quite uncertain with a broad range of unit costs between the higher and lower values. As long as these ranges are wide enough to encompass the ultimate unit cost achieved for the Nth-of-a-kind steady state system, the range in cost difference calculated from using the difference in levelized quantities will bound the actual cost difference between these fuel cycle options for the Nth-of-a-kind steady state system. For example, if there is a 1 mill/kWe-hr difference, whether first fuel cycle option turns out to have a levelized cost of 40 mills/kWe-hr or 70 mills/kWe-hr, the second option will always be exactly 1 mill/kWe-hr higher than that. For the more realistic analysis, this will be a range that can be narrow (nearly identical options) to very wide for options that utilize very different technology, particular reactor technologies.

The following is a more formal development of the underlying mathematics utilized in this methodology for comparing the estimated LCAE. The levelized cost of electricity at equilibrium (LCAE) is calculated as the linear summation of the levelized units (α) of each component for that fuel cycle option multiplied by the unit cost (C) of that component. The details of these calculations are included in Appendix C-9 This is represented in Equation D-2.22.1.

$$LCAE_x = \sum_{i=1}^{N} \alpha_{x,i} C_i \tag{D-2.22.1}$$

Calculation of the difference in cost is the difference between the two LCAE calculations. This is shown in Equation D-2.22.2 where BOC is the Basis of Comparison.

$$\Delta_{x,BOC} = LCAE_x - LCAE_{BOC} = \sum_{i=1}^{N} \alpha_{x,i} C_i - \sum_{i=1}^{N} \alpha_{BOC,i} C_i = \sum_{i=1}^{N} C_i \left(\alpha_{x,i} - \alpha_{BOC,i} \right) \tag{D-2.22.2}$$

For simplicity, Equation D-2.22.2 is rewritten where the cost differences from each component is defined by Equation D-2.22.3, putting Equation D-2.22.2 into the final form given in Equation D-2.22.4.

$$\Delta^i_{x,BOC} = C_i \left(\alpha_{x,i} - \alpha_{BOC,i} \right) \tag{D-2.22.3}$$

$$\Delta_{x,BOC} = \sum_{i=1}^{N} \Delta^i_{x,BOC} \tag{D-2.22.4}$$

Equation D-2.22.4 can then be solved to determine the range of cost difference for the fuel cycle option relative to the BOC determining the upside (low), downside (high), and mean from the data provided in the AFCCBR without the need to solve Equation D-2.22.2 by running a very large number of histories to sample the highly simplified (and clearly assumed for practical reasons) unit cost distributions.

The upside potential (minimum cost difference) of the fuel cycle option of interest relative to the BOC is solved from Equation D-2.22.5 based on the definitions in Equation D-2.22.6, D-2.22.7, and D-2.22.8. Equation D-2.22.8 being where much of the power of this method is derived. Independent of the magnitude or uncertainty in the unit cost of these items, there is no potential for a difference in cost if the options being compared use the exact same quantities regardless of the magnitude of the cost and uncertainty.

$$\Delta_{x,BOC}^{\min} = \sum_{i=1}^{N} \Delta_{x,BOC}^{i,\min} \tag{D-2.22.5}$$

$$\text{if } \alpha_{x,i} - \alpha_{BOC,i} < 0 \text{ then } \Delta_{x,BOC}^{\min} = C_i^{\max}\left(\alpha_{x,i} - \alpha_{BOC,i}\right) \tag{D-2.22.6}$$

$$\text{if } \alpha_{x,i} - \alpha_{BOC,i} > 0 \text{ then } \Delta_{x,BOC}^{\min} = C_i^{\min}\left(\alpha_{x,i} - \alpha_{BOC,i}\right) \tag{D-2.22.7}$$

$$\text{if } \alpha_{x,i} - \alpha_{BOC,i} = 0 \text{ then } \Delta_{x,BOC}^{\min} = \Delta_{x,BOC}^{mean} = \Delta_{x,BOC}^{\max} = 0 \tag{D-2.22.8}$$

The downside potential (maximum cost difference) of the fuel cycle option of interest relative to the BOC is solved from Equation D-2.22.9 based on the definitions in equation D-2.22.8, D-2.22.10, and D-2.22.11.

$$\Delta_{x,BOC}^{\max} = \sum_{i=1}^{N} \Delta_{x,BOC}^{i,\max} \tag{D-2.22.9}$$

$$\text{if } \alpha_{x,i} - \alpha_{BOC,i} < 0 \text{ then } \Delta_{x,BOC}^{\max} = C_i^{\min}\left(\alpha_{x,i} - \alpha_{BOC,i}\right) \tag{D-2.22.10}$$

$$\text{if } \alpha_{x,i} - \alpha_{BOC,i} > 0 \text{ then } \Delta_{x,BOC}^{\max} = C_i^{\max}\left(\alpha_{x,i} - \alpha_{BOC,i}\right) \tag{D-2.22.11}$$

The mean difference of the fuel cycle option of interest relative to the BOC is solved from Equation D-2.22.12.

$$\overline{\Delta}_{x,BOC} = \sum_{i=1}^{N} \overline{\Delta}_{x,BOC}^{i} = \overline{LCAE_x} - \overline{LCAE_{BOC}} \tag{D-2.22.12}$$

This analysis is all based on the validity of the range of unit cost data. By looking at the potential difference for each component and the range of unit cost used for that component, it is very easy and straightforward to expand the range or do other analyses to test the robustness of this range of cost difference. Unit costs are treated as independent variables. This range is exact if all variables can be at the necessary extremes simultaneously. If they cannot, the range is reduced. This is particularly important when different reactor technologies must be used. This will be discussed later where a simple rationale approach is proposed to reduce the range to more realistic spreads in the reactor costs. Unlike all of the other metrics that were evaluated, it was necessary to make specific assumptions about technology (which unit cost numbers would be used) for each step in the fuel cycle option modeled or at least assumptions about when the technology used would result in a different unit cost distribution.

Adjustments to the LCAE Data

An objective for conducting this Study was to identify the best performance for a given Evaluation Group relative to the Basis of Comparison. In order to do this, it was necessary to examine each Evaluation Group and the results from the Analysis Example and make adjustments as necessary to ensure that the performance was reflective of what is best for that metric. The LCAE for the Analysis Example does provide the results for that choice of reactor technology for options within the Evaluation Group. The approach taken in using the LCAE information for the Evaluation and Screening was to look for results that are close to the current U.S. fuel cycle, since if the Analysis Example performs at least that well, one can conclude that options exist within that Evaluation Group that could have similar costs for electricity production as using today's U.S. fuel cycle. (As a side note, the LCAE for the current U.S. fuel cycle as represented by EG01 is the LCAE for continuing to build new reactors in place of existing ones as they reach their end-of-life. Many reactors operating today have the original construction costs fully amortized, so that these costs are not part of the current electricity generation cost.)

In the case of the LCAE, the unit cost range for all thermal reactors shows that a LWR should be used in the case of fuel cycle options that utilize thermal reactor technology. The Analysis Example for EG02 and EG05 assumed an HTGR in the original LCAE analysis. These fuel cycle options can be implemented with exist LWR technology. Given that the HTGR cost distributions are skewed to higher cost, these fuel cycle options were adjusted to utilize the lower cost LWR technologies. In addition to using LWR instead of HTGR technology, the cost range of fabrication of LWR fuel is far less than for fabrication HTGR fuel and this adjustment was also made. No change to mass flow were considered and were assumed to be small. The total effect was to reduce the mean LCAE for both EG02 and EG05 by approximately 20 mills/kWe-hr by using an LWR.

As noted above and in Appendix C-9, there are several challenges associated with using the LCAE results listed in Table D-2.22.1. A critical aspect is that the estimates for LCAE are obtained for the Analysis Examples that utilized a wide variety of technologies for the reactor, critical or sub-critical. Unlike the other metrics, the question of whether or not the LCAE for the Analysis Example fairly represents the performance of the Evaluation Group is very difficult, if not impossible, to answer since the calculation of LCAE depends on many parameters related to choices of technologies for the fuel cycle. The challenge in using the LCAE results is to appropriately inform on the Evaluation Group, not the Analysis Example.

Since the Evaluation and Screening is a comparative evaluation with respect to the current U.S. fuel cycle, the interpretation of the LCAE results focused on the difference with EG01 rather than on the LCAE itself. Figure D-2.22.2 plots the differences between EG01 and the other Evaluation Groups (in mils/kWh or $/MWh). The Evaluation Groups are ordered by the mean calculated difference between the Evaluation Group and EG01, with lower mean cost on the left and higher mean cost on the right.

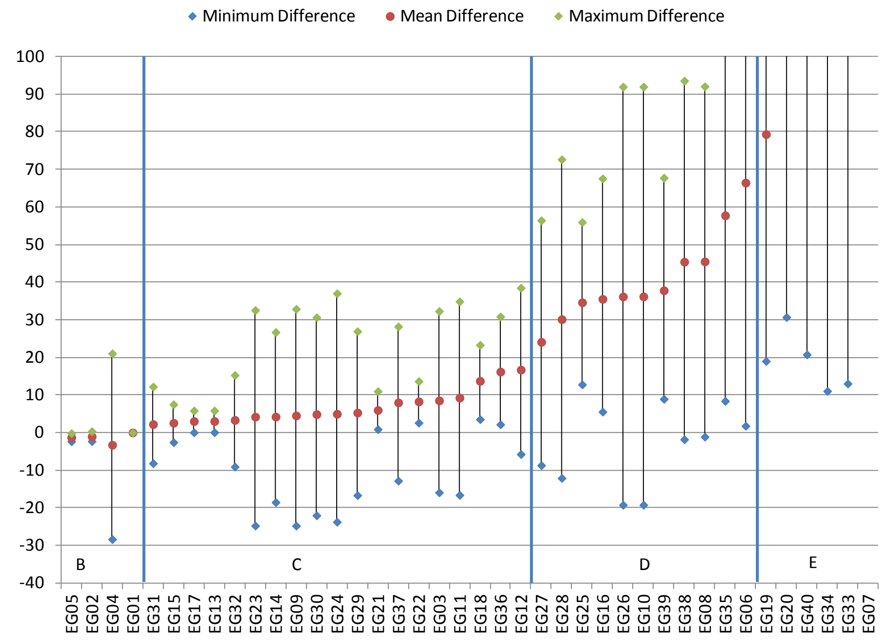


Figure D-2.22.2. Difference in LCAE in Mils per kW-hr for the Analysis Example of Each Evaluation Group and the Analysis Example of EG01, Ordered by Increasing Positive Difference.

For each Analysis Example, the end points of the differences in the uncertainty distributions are also shown, given by the minimum difference between the uncertainty distribution for an Analysis Example and the uncertainty distribution for EG01 and the maximum difference. For many of the Analysis Examples, this range of differences includes the point where LCAE would be the same as the mean calculated for EG01, indicating a possibility that the electricity production costs could be the same.

Figure D-2.22.2 shows the current U.S. fuel cycle, EG01, as being fourth from the left, with the Analysis Example for three other Evaluation Groups, EG02, EG04, and EG05 having an estimated mean calculated LCAE that is marginally lower. Moving to the right of EG01, there are a number of Evaluation Groups whose mean calculated LCAE appears to be "similar" than EG01, where "similar" is defined as having a mean calculated LCAE that is up to about 30% higher than EG01 and at the same time has a possibility of having an LCAE about the same as EG01. Further to the right, the Analysis Examples appear to have a mean LCAE that is clearly higher than for EG01, and there is little or no likelihood that the Analysis Example LCAE would approach EG01. It must be emphasized that part of this difference was caused by the choice of reactor for the Analysis Example, which in some cases led to higher LCAE for one Analysis Example compared to another even though the fuel cycles were similar. An example of this is the difference between EG07 and EG06 (or EG08). Both Evaluation Groups have sub-critical reactors, but in EG07 an accelerator-driven system was used, while EG06 and EG08 used a fusion-fission hybrid. The difference in cost is partly a reflection of the accelerator requiring power to operate while the fusion part of a fusion-fission hybrid may produce power, which has a large effect on the power production by the system. If EG07 had also used a fusion-fission hybrid, the LCAE for EG06, EG07, and EG08 would all be comparable.

With this understanding of the value and limitations of the Analysis Example information, the results on Figure D-2.22.2 were divided into several bins, just as was done for all of the other metrics. The bin boundaries are shown on Figure D-2.22.2 and are listed in Table D-2.22.2.

Table D-2.22.2. Bin Descriptions for the LCAE of the Analysis Examples.

Bin	Bin Description for Using the Analysis Example LCAE
A	**Likely to be Lower than the Current U.S. Fuel Cycle** - The LCAE for the Evaluation Group is likely to be lower than EG01. Placement in this bin requires the Analysis Example to have both a mean LCAE and uncertainty difference lower than that of EG01.
B	**Likely to be Comparable to the Current U.S. Fuel Cycle** - The LCAE for the Evaluation Group is likely to be comparable to EG01. Placement in this bin requires the Analysis Example to have a mean LCAE that is comparable to that of EG01 and the uncertainty differences also include the mean LCAE for EG01. Basis of Comparison is in this bin.
C	**Likely to be "Similar" to the Current U.S. Fuel Cycle** – The LCAE for the Evaluation Group is likely to be within about 30% of the LCAE for EG01. Placement in this bin requires the Analysis Example to have a mean LCAE that is no larger than about 30% greater than EG01 and the uncertainty difference includes (or is close to including) the mean LCAE for EG01.
D	**Likely to be Higher than the Current U.S. Fuel Cycle** – The LCAE for the Evaluation Group is likely to be more than 30% higher than the LCAE of EG01. Placement in this bin requires the Analysis Example to have a mean LCAE that is more than 30% greater than the LCAE of EG01 and the uncertainty difference includes (or is close to including) the mean LCAE for EG01.
E	**Likely to be Much Higher than the Current U.S. Fuel Cycle** – The LCAE for the Evaluation Group is likely to be more than 100% higher than the LCAE of EG01. Placement in this bin requires the Analysis Example to have a mean LCAE that is more than 100% greater than the LCAE of EG01 and the uncertainty difference does not include the mean LCAE for EG01.

The bin boundaries were determined by examining the LCAE results for the Analysis Examples and observing "breaks" in the data for both the mean LCAE and the uncertainty differences. The Evaluation Groups were placed in the appropriate bin according to the bin guidelines.

The final Metric Data for the 40 Evaluation Groups are provided in Figure D-2.22.3 (using the data from Table D-2.22.1 and Figure D-2.22.2) with the Evaluation Groups plotted in numerical order from left to right to emphasize the relative performance of once-through, limited recycle, and continuous recycle fuel cycles.

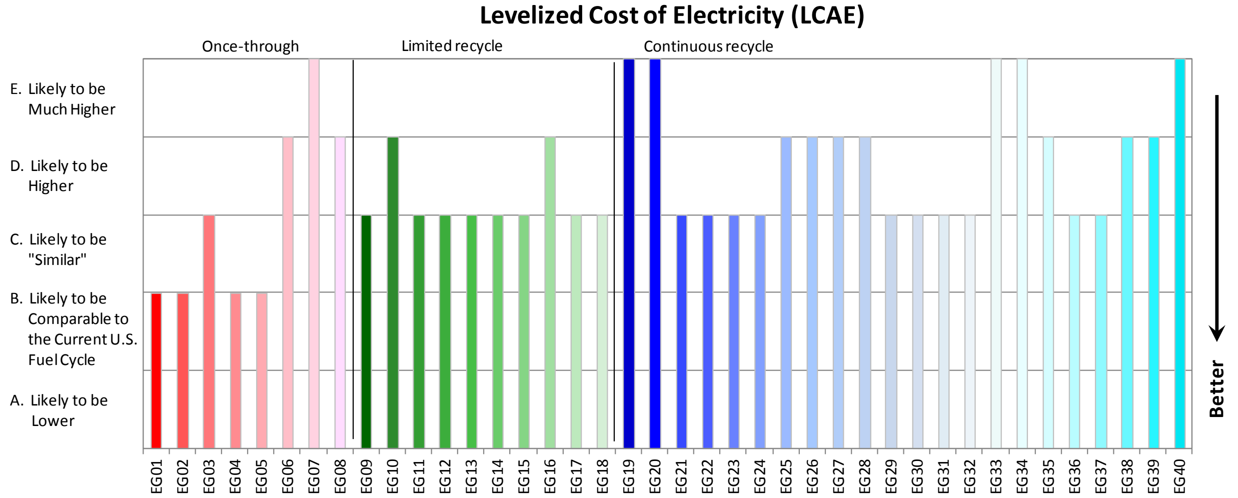


Figure D-2.22.3. Metric Data for LCAE for the 40 Evaluation Groups Ordered by Evaluation Group Number.

Metric Observations

The Levelized Cost at Equilibrium (LCAE) is the metric for Financial Risk and Economics, one of the "challenge" criteria as described in Appendix A. As a consequence, this is a metric for which promising Evaluation Groups were not considered since all fuel cycle options will face challenges in achieving an LCAE comparable to that for the Basis of Comparison. However, based on a ranking of the Evaluation Groups by bin, observations of the Evaluation Groups based on the LCAE Metric Data are as follows:

- Starting with EG01, most Evaluation Groups in bins B and C could have an LCAE "similar" to EG01.
- Many of the promising options identified for other Evaluation Metrics are in bin B or C, indicating that the anticipated cost of electricity production could be similar enough to the current U.S. fuel cycle.

Detailed comparison of the cost breakdown for Analysis Examples EG23, EG24, EG29 and EG30.

Since the LCAE is not used in conjunction with other metrics, but is provided separately as additional information, it is instructive to examine the differences in LCAE for the best performing Evaluation Groups as listed in the Main Report. Figure D-2.25.4 shows the main cost contributions to the estimated mean LCAE for Analysis Examples EG23, EG24, EG29 and EG30 and compared directly to the cost contributions of EG01. The Analysis Examples EG23 and EG24 are fast reactors operating on a closed Pu and TRU cycle, respectively, that are self-sufficient on Pu and TRU production. The Analysis Examples EG29 and EG30 are, respectively, net Pu and TRU producing fast reactors that breed sufficient excess Pu to supply thermal reactors operating on a closed Pu cycle. While the O&M costs are about the same for all 5 systems, the charges for capital cost recovery are, as expected, higher for EG23 and EG24 which use only fast reactors. Evaluation Groups EG29 and EG30, which involve a combination of fast and thermal reactors, have capital cost recovery charges that are proportional to the fraction of each reactor type utilized in the system.

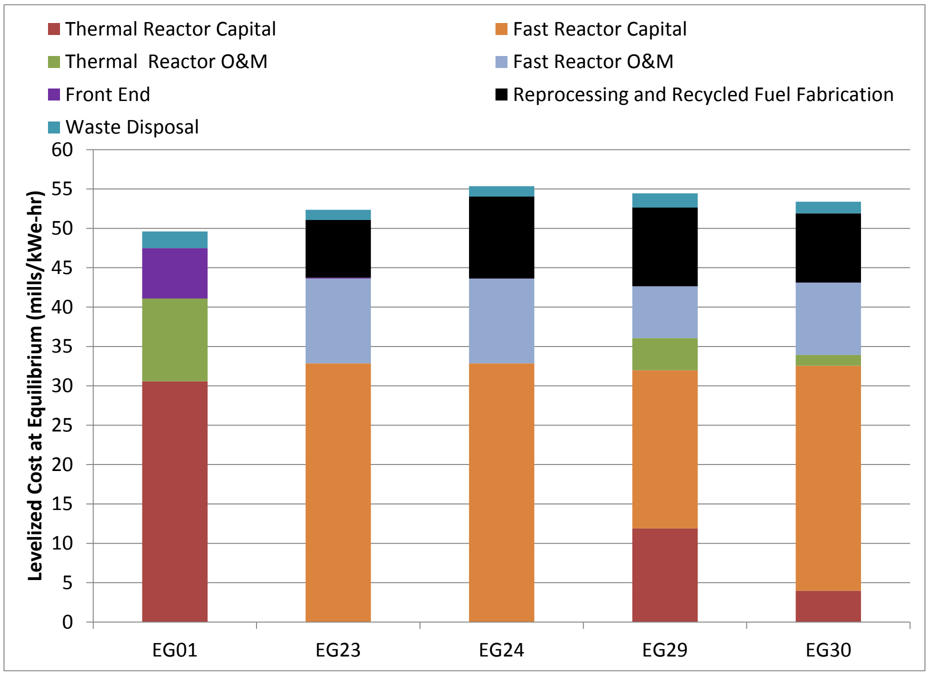


Figure D-2.22.4. Comparison of the Electricity Cost Breakdown for EG01, EG23, EG24, EG29 and EG30, Averages of the Calculated Values.

The ultimate relative costs of building and operating thermal reactors and fast reactors is critical to understanding the relative costs of the fuel cycle options which can operate with a variable fraction of these two reactor types (e.g., EG29 and EG30). A higher breeding ratio results in a higher equilibrium fraction of thermal reactors which explains much of the difference between the Analysis Examples used for EG29 and EG30. These Analysis Examples will approach the results for the Analysis Examples of EG23 and EG24, respectively, as the breeding ratio is reduced to the breakeven point.

The “Fuel Costs” (i.e. fuel cycle costs which are not reactor O&M and reactor capital) are further broken down in Table D-2.22.3 and in Figure D-2.22.5.

Table D-2.22.3. Break-down of the Fuel Cost Contributions to the Estimated Mean LCAE for EG01, EG23, EG24, EG29 and EG30.

	EG01	EG23	EG24	EG29	EG30
U ore	3.36	0.019	0.021	0.024	0.020
U Conversion	0.30	0	0	0	0
U Enrichment	1.72	0	0	0	0
Fresh fuel fabrication	0.94	0	0	0	0
DU deconversion	0.34	0	0	0	0
Reprocessing	0	1.53	1.97	2.53	2.27
Fab of Reprocessed fuel	0	5.28	8.40	6.69	6.07
HLW conditioning	0	0.641	0.699	0.784	0.658
HLW disposal	0	0.640	0.698	0.783	0.657
SNF condit. before transp.	0.23	0.13	0.12	0.21	0.16
SNF disposal	1.41	0	0	0	0
Total	8.30	8.24	11.91	11.02	9.53

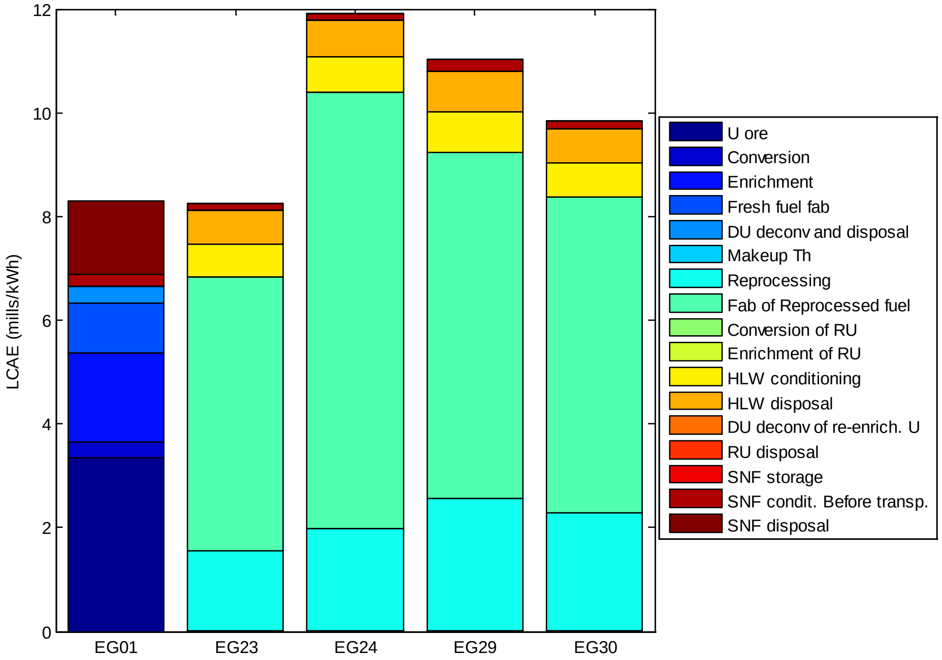


Figure D-2.22.5. Break-down of the Non-reactor Fuel Cycle Cost Contributions to the Estimated Mean LCAE for EG01, EG23, EG24, EG29 and EG30.

While similar in overall magnitude, the fuel costs of EG01 and EG23 are due to very different processes. While for EG01 the largest fuel cost charges are for procurement of uranium ore and enrichment services, for EG23, EG24, EG29 and EG30 the largest charges are for the fabrication of the recycled fuel, followed by the cost of reprocessing. The combined cost of HLW conditioning (which is sometimes included in the reprocessing cost, since it is incurred at the separation facility, but here is shown separately to be more informative) and HLW disposal, is about the same as that of direct SNF disposal. The “SNF conditioning before transportation” charges are incurred independently of whether the fuel is shipped to a repository or to a reprocessing facility. Additionally, it is noted that small charges for the procurement of uranium ore are incurred also by EG23, EG24, EG29 and EG30, but they are too small to be visible in Figure D-2.22.5 although one can see the values for these in Table D-2.22.3.

The cost of re-fabrication of reprocessed fuel in EG23 is dominated by the re-fabrication of the driver fuel which, because of the presence of plutonium, requires glove box handling. Reprocessing, albeit expensive, gives a smaller contribution than recycled fuel fabrication. This may seem counterintuitive to those who are used to seeing the cost of recycling PWR-LEU to produce PWR-MOX fuel: in that case the reprocessing costs are higher than the MOX fabrication costs because about 9 kg of PWR-LEU fuel must be reprocessed to produce 1 kg of PWR-MOX fuel. However, for reprocessing and refabrication of recycled fuel of EG23, EG24 EG29 and EG30, the ratio of fuel reprocessed to recycled fuel fabricated is close to one-to-one.

In the case of EG24, the re-fabrication of remote-handled reprocessed fuel is substantially more expensive than for EG23, because of the presence of MA. In the case of EG29, Pu only is recycled, as in EG23, but all the components of the fuel costs are more expensive than in EG23, especially fuel re-fabrication and reprocessing. This penalty is due to the presence of the LWR, which has a substantially lower burnup than the SFR driver, thus requiring a heavier reliance on the fuel reprocessing and refabrication services per unit of energy produced. Therefore, while the unit costs (in $/kgHM) for the fuel fabrication are assumed the same for the two fuel types, the PWR charges incurred for those services per unit energy produced (i.e. in mills/kWh) are more than twice those incurred by the SFR (i.e. 10.8 mills/kWh for the refabrication of the PWR fuel versus 4.0 mills/kWh for the refabrication of the SFR fuel, weighted by the share of power produced by the driver and by the blanket).

The situation is different in the case of EG30 but in this case the SFR is operated on TRU and the LWR feed contain Pu and traces of MA. Also, the LWR fraction in EG30 is only 13%, versus almost 40% in the case of EG29 because of differences in the breeding ratio in the Analysis Examples. This explains the somewhat counterintuitive drop in fuel cycle costs of EG30 as compared to EG29. But, why are the reprocessing and refabrication costs lower for EG30 as compared to EG24? In both cases, all the TRU are recycled, and in the case of EG30 there is an LWR which tends to increase the fuel cycle costs, as we have discussed above. The reason is the presence of the blanket in the case of the fast reactor of EG30, which reduces the need for expensive remote fabrication of TRU-containing fuel to the driver only, which has a smaller mass and a longer core residence time: the driver of EG30 weights 13.6 MT and resides in the core for 4.9 EFPY, as opposed to a mass of 16.7 MT and fuel residence time of 3.6 EFPY for the entire core of EG24. This cost reduction is only available for the re-fabrication part, but not for the reprocessing, which in fact is more expensive for EG30 than for EG24: both the blanket and the driver need reprocessing, and an additional penalty is derived by the presence of the LWR, which achieves a lower burnup.

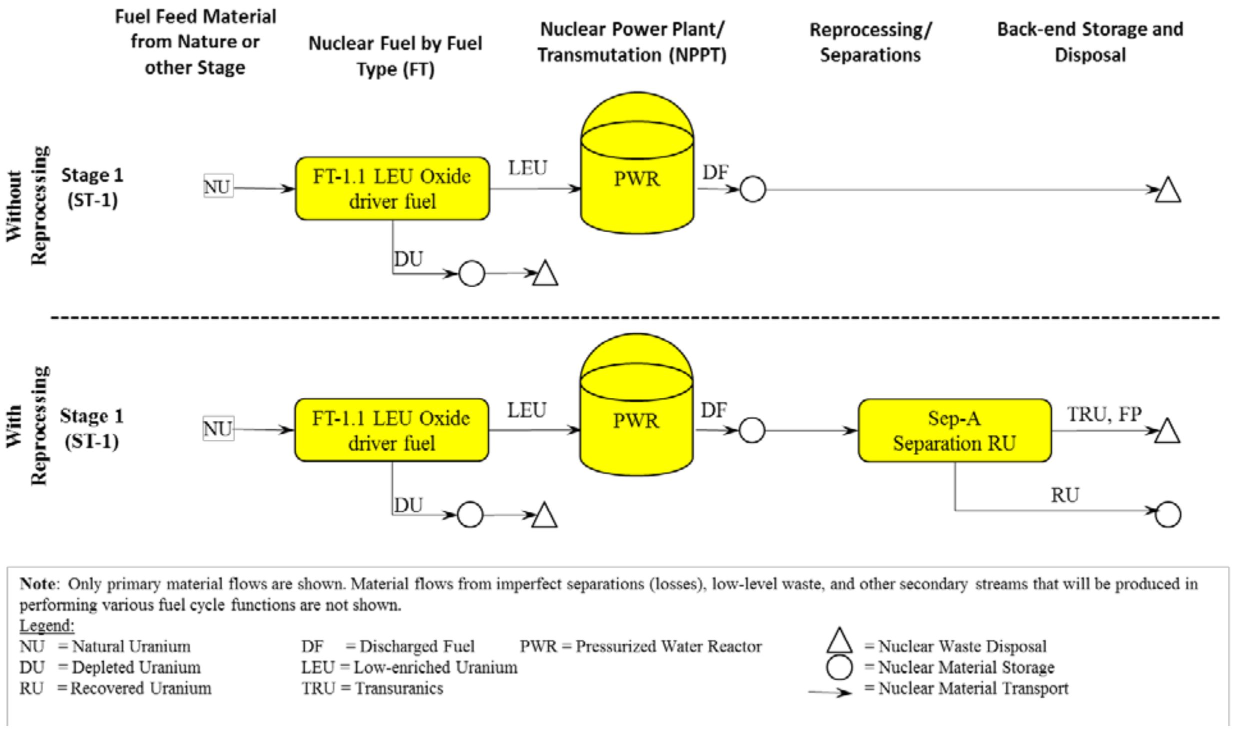
D-3 General Fuel Cycle Issues

This section discusses the results on issues that would apply to most, if not all fuel cycles. Three issues were examined as described in the following sections.

D-3.1 Impact of Used Fuel Processing in Once-through Fuel Cycle Option

In a typical once-through fuel cycle option, it is assumed that the discharged fuel from the reactors is directly disposed without the processing or separation of the discharged fuel. However, since processing of the discharged fuel affects the nuclear waste management metrics, the potential impacts of processing spent fuel that is destined for disposal to alter the waste characteristics were evaluated using EG01, the Basis of Comparison, which is a once-through fuel cycle. For consistency of presentation and to connect results to those of the 40 Evaluation Groups, in what follows, the material sent to waste disposal is referred to as SNF+HLW, even though the basis of comparison without processing sends SNF to disposal, and with processing, sends HLW to disposal. This is because the waste mass and activity metrics used for the Evaluation and Screening are for SNF+HLW; DU+RU+RTh mass is also used.

Figure D-3.1.1 shows the material flow diagram for EG01 with and without processing/separations of used nuclear fuel. As displayed in the upper material flow diagram in Figure D-3.1.1, the discharged fuel is directly disposed as in a typical once-through fuel cycle option, while with processing of the spent fuel prior to disposal, the uranium is separated and disposed as part of DU+RU, and the TRU and FP are disposed as HLW, as shown in the lower material flow diagram.



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

Figure D-3.1.1. Material Flow Diagram of EG01 With and Without Processing of Used Nuclear Fuel.

For the Basis of Comparison EG01, the SNF+HLW mass is ~22 t/GWe-yr (see Table D-3.1.1), which is all SNF. However, the SNF+HLW mass of EG01 could be reduced significantly by separating uranium from the waste stream. The SNF+HLW mass and activity of EG01 with and without processing of the discharge fuel are provided in Table D-3.1.1 for an assumed separation efficiency of 99%. The variations of the SNF+HLW mass and activity with separation efficiency are summarized in Tables D-3.1.2 and D-3.1.3 and plotted in Figures D-3.1.2 and D-3.1.3, respectively.

Table D-3.1.1. HLW Mass and Activity of EG01 With and Without Processing.

Waste Management Information		**Discharged Fuel**	**No Processing**	**Processing with Separation Efficiency of 99%**	
			SNF+HLW	**Recovered**	**HLW**
Mass (t/GWe-yr)	Total	21.92	21.92	20.28	1.64
	- U	20.49		20.28	[a] 0.21
	- TRU	0.29		-	0.29
	- FP	1.14		-	1.14
Activity, MCi/GWe-yr	10 years		12.71	12.71	
	100 years		1.34	1.34	
	100,000 years		0.00165	0.00147	

a) 1% of loss in processing/separation was assumed

b) The basis of comparison only has SNF; with fuel processing HLW is produced

Table D-3.1.2. Masses of SNF+HLW and DU+RU of EG01 With and Without UNF Processing as a Function of Separation Efficiency.

Separation Efficiency (%)	**No Separations***	**95**	**98**	**99**	**99.90**	**99.99**
Mass of SNF+HLW (t/GWe-yr)	21.92	2.454	1.840	1.635	1.450	1.432
- U	-	1.024	0.410	0.205	0.020	0.002
- TRU	-	0.287	0.287	0.287	0.287	0.287
- FP	-	1.143	1.143	1.143	1.143	1.143
Mass of DU+RU (t/GWe-yr)	166.7	186.1	186.7	186.9	187.1	187.1
- RU	-	19.46	20.08	20.28	20.47	20.48

*The basis of comparison only has SNF; with fuel processing HLW is produced.

Table D-3.1.3. Activity of SNF+HLW for EG01 With and Without UNF Processing as a Function of Separation Efficiency.

Separation Efficiency (%)	**Activity of HLW (Curies/GWe-yr)**		
	10	**100**	**100,000**
95	1.27E+07	1.34E+06	1.47E+03
98	1.27E+07	1.34E+06	1.47E+03
99	1.27E+07	1.34E+06	1.47E+03
99.90	1.27E+07	1.34E+06	1.46E+03
99.99	1.27E+07	1.34E+06	1.46E+03
No Separation	1.27E+07	1.34E+06	1.65E+03

*The basis of comparison only has SNF; with fuel processing HLW is produced.

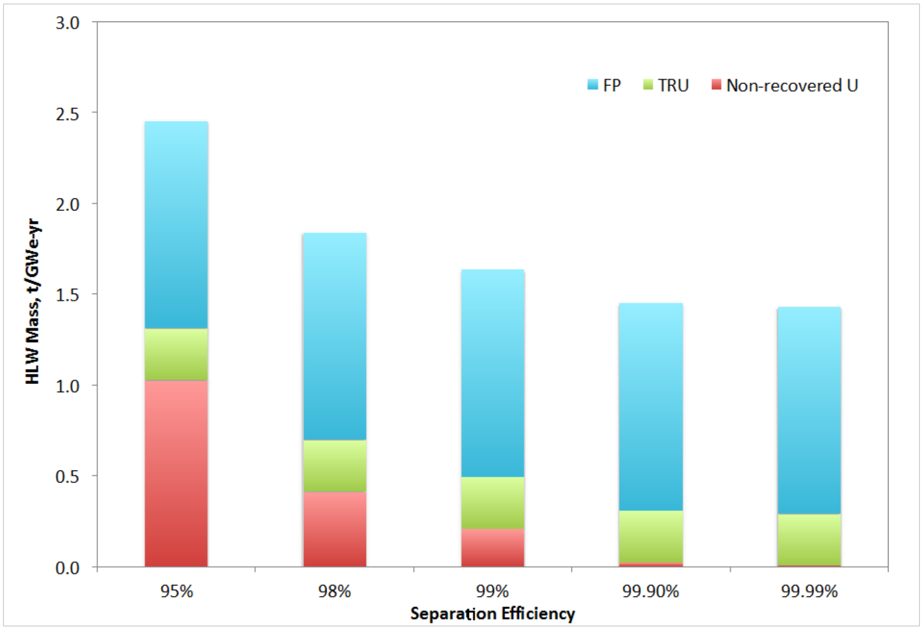


Figure D-3.1.2. Impact of Separation Efficiency on Mass of HLW for EG01 With Fuel Processing.

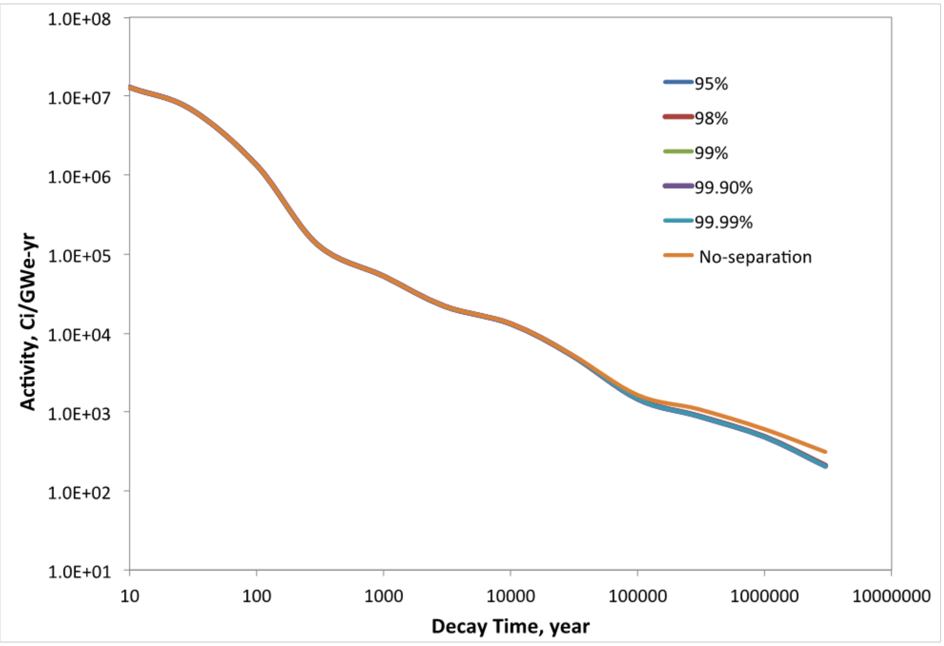


Figure D-3.1.3. Impact of Separation Efficiency on Activity of SNF+HLW for EG01 With Fuel Processing.

Since uranium is the dominant element in the discharged fuel of the Analysis Example for EG01, the processing of the discharged fuel decreases the SNF+HLW mass significantly. The SNF+HLW mass of the fuel decreases to 1.64 t/GWe-yr (from 22 t/GWe-yr) with a separation efficiency of 99% and further reductions are observed with higher separation efficiencies. However, the fuel processing has no impact on the HLW activity at 10 and 100 years after discharge, as shown in Table D-3.1.3 and Figure D-3.1.3 because the contribution of the recovered uranium to the activity is negligibly small compared to the TRU and FP. At 100,000 years after discharge, some change in the HLW activity is observed. It should be noted that the change in the SNF+HLW activity would be more noticeable for thorium-fueled once-through fuel cycle options in this time period due to the higher contributions from the thorium decay products to the SNF+HLW activity. Beyond 100,000 years, the difference in activity becomes more noticeable as the radioactive products from uranium decay build up with time. Results in Table D-3.1.3 also show that the separation efficiency has very small impact on the activity at 10, 100, and 100,000 years.

The processing of the spent nuclear fuel however increases the amount of DU+RU+RTh to be disposed by ~12% (Table D-3.1.2). This is due to the increase in RU mass to about ~20 t/GWe-yr with processing; it is zero for unprocessed fuel. The volume of low level waste also increases with the approach due to the processing of the fuel. This approach also brings in the development cost and time for the processing technologies and waste fabrication, along with the deployment time because of the need for the separations and waste production facilities. Table D-3.1.4 contains the comparison of Evaluation and Screening metric data for the EG01 options with and without fuel processing (99% separation efficiency).

Table D-3.1.4. Comparison of Metric Data for EG01 Without and With UNF Processing (Bin and Bin Description).

Metric	**EG01without processing**	**EG01 with processing**
Development time	Bin A. No Devel. Needed	Bin C. 5-10 yrs
Development cost	Bin A. No Devel. Needed	Bin C. \$200M - \$2B
Deployment costs	Bin A. No FOAK Needed	Bin D. \$10 B to \$25 B
Compatibility with existing infrastructure	Bin A. Compatible - >90%	Bin B. Mostly Compatible - > 50% but < 90%
Existence of regulations for the fuel cycle & familiarity with licensing	Bin A. U.S. Regs/ Familiarity exists and applied	Bin C. Non-U.S. Regulations/ Familiarity exists
Existence of market incentives and/or barriers to commercial implementation	Bin A. Mkts exist; Low Cap risk; Incent in place	Bin C. Mkts weak; Low Cap risk; No gvt invest
Land Use per energy generated	Bin B. 0.1 - 0.2 km^2/GWe-yr	Bin B. 0.1 - 0.2 km^2/GWe-yr
Water Use per energy generated	Bin B. 15,000 - 30,000 ML/GWe-yr	Bin B. 15,000 - 30,000 ML/GWe-yr
Radiological exposure	Bin B. Total worker dose of 0.5 – 5.0 person-Sv/Gwe-yr	Bin B. Total worker dose of 0.5 – 5.0 person-Sv/Gwe-yr
Carbon Emissions	Bin B. 30 - 60 kt/GWe-yr	Bin B. 30 - 60 kt/GWe-yr
Levelized Cost of Electricity at Equilibrium (LCAE)	-	-
Mass of SNF + HLW	Bin E. 12 to <36 t/GWe-yr	Bin A. < 1.65 t/GWe-yr
Activity of SNF + HLW at 100yrs	Bin C. 1.05 to <1.6 MCi/GWe-yr	Bin C. 1.05 to <1.6 MCi/GWe-yr
Activity of SNF + HLW at 100,000yrs	Bin C. 1.0×10^{-3} to $<2.3 \times 10^{-3}$ MCi/GWe-yr	Bin C. 1.0×10^{-3} to $<2.3 \times 10^{-3}$ MCi/GWe-yr
Mass of DU+RU+RTh disposed	Bin E. 120 to <200 t/GWe-yr	Bin E. 120 to <200 t/GWe-yr
Volume of LLW disposed	Bin C. 252 to <634 m^3/GWe-yr	Bin D. 634 to <1592 m^3/GWe-yr

Metric	EG01without processing	EG01 with processing
Material attractiveness – normal operating conditions	unattractive	unattractive
Activity of SNF + HLW at 10yrs	highly radioactive	highly radioactive
Natural uranium required per unit of energy production	Bin D. > 145 t/GWe-yr	Bin D. > 145 t/GWe-yr
Natural thorium required per unit of energy production	Bin A. <3.8 t/GWe-yr	Bin A. <3.8 t/GWe-yr
Challenges of Addressing Safety Hazards	Bin C. Potentially Similar in Challenge	Bin C. Potentially Similar in Challenge
Safety of the Deployed System	Bin A. Yes	Bin A. Yes

D-3.2 Impact of Separation Efficiency

High level waste (HLW) consists of materials intentionally separated for disposal as waste and the losses of desired product materials from the reprocessing of used nuclear fuel and fabrication of recycle fuel. It is noted that the 40 Analysis Examples considered for the Evaluation and Screening were calculated assuming a separation efficiency of 99%. In order to assess the impact of the separation efficiency on the nuclear waste masses and activity, a sensitivity study in which the separation efficiency value varied from 95% to 99.99% was performed using the Analysis Example for EG32.

The Analysis Example for EG32 is a two-stage continuous recycle case. The first stage contains Pressurized Water Reactors (PWRs) with enriched-uranium oxide fuel, representing the design and performance of typical PWRs utilizing commercially-supplied low enriched uranium fuel with an average discharge burnup of 50.0 GWd/t. The used nuclear fuel of Stage 1 is reprocessed and the recovered TRU material is used as part of the feed fuel for Stage 2. The recovered uranium (RU) from the Stage 1 used fuel is utilized in Stage 2 as needed, and the extra recovered uranium is sent to waste disposal. The actinide losses during reprocessing and the fission products are also part of the waste.

Sodium-cooled Fast Reactors (SFRs) with TRU/RU fuel are used in Stage 2. The average burnup is 132 GWd/t and the TRU conversion ratio is ~0.5. The recovered TRU and RU from the discharged fuel are recycled back into Stage 2, while the recovered TRU and RU from stage 1 are used as makeup feed. The actinide losses during fuel separations and the fission products become part of the waste.

The calculated waste mass and activity of EG32 for separation efficiencies from 95% to 99.99% are provided in Table D-3.2.1. For the separation efficiency of 99%, the electricity power sharing for Stage 1 and Stage 2 are 67.8% and 32.2%, respectively (see Table D-1.1). This power sharing is adjusted with change in the separation efficiency in order to account for the change in the recovered TRU mass and the TRU mass balance between the stages.

Since most of the actinides are continuously recycled in the Analysis Example for EG32, the fission products (FP) are the dominant contributors to the nuclear waste mass. The minor variation in the FP mass in Table D-3.2.1 is due to the change in the electricity-sharing between Stages 1 and 2 as separations efficiency is changed. The actinide loss masses decrease as the separation efficiency increases and as a result, the nuclear waste (SNF+HLW) mass ranges between 1.153 t/GWe-yr and 2.012 t/GWe-yr (the only HLW mass in table).

The activity profiles are plotted in Figure D-3.2.1. Since the FP contribution is dominant for few hundred years after discharge, the activity is comparable regardless of the separation efficiencies. However, noticeable differences in the activity are observed after a few hundred years because the TRU mass, which is the dominant contributor to the activity after all fission products have decayed out, varies as the separation efficiency is changed.

Table D-3.2.1. Waste Masses and Activity Variation with Separation Efficiency for EG32.

		95%	98%	99%	99.9%	99.99%
Mass, t/GWe-yr	SNF+HLW	2.012	1.486	1.318	1.168	1.153
	- U	0.811	0.314	0.155	0.015	0.002
	- TRU	0.042	0.018	0.009	0.001	0.000
	- FP	1.159	1.155	1.154	1.152	1.152
	DU+RU	134.8	129.2	127.2	125.2	125.0
Activity, MCi/GWe-yr	10 years	9.88	9.70	9.64	9.58	9.58
	100 years	1.11	1.09	1.08	1.07	1.07
	100,000 years	6.6E-04	5.5E-04	5.2E-04	4.9E-04	4.8E-04

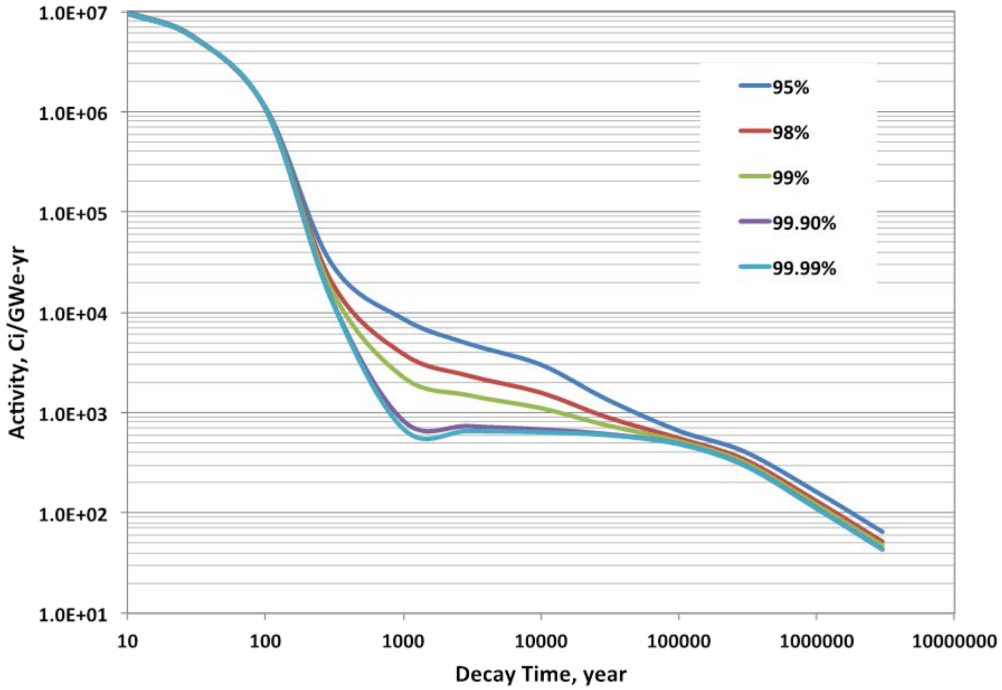


Figure D-3.2.1. Activity of SNF+HLW for Analysis Example of EG32 for Different Separation Efficiency Values.

D-3.3 Impact of Extended Decay Storage on Fuel Cycles

In a fuel cycle, extended decay storage of spent nuclear fuel (SNF) or used nuclear fuel (UNF), products, or wastes can be used to slowly reduce radiation level by radioactive decay to potentially reduce worker exposure or shielding requirements, but the remaining radiation would still necessitate remote handling of the materials. In once-through fuel cycles, storage is used as part of a fuel cycle strategy to allow short-lived radionuclides to decay, affecting radiation and decay heat. Extended decay storage in spent fuel pools or dry casks can favorably impact SNF / UNF handling and processing as well as SNF, HLW, and LLW disposal requirements. Extended decay storage prior to disposal of the SNF is a potential option for any once-through fuel cycle. It provides benefits for the planning and logistics of waste management due to the added time delay prior to disposal (more time to plan), reduces decay heat, and facilitates SNF handling due to the reduced radiation from radioactive decay. However, if extended decay storage is used, the storage capacity may have to extend well beyond the life of the power plant, likely necessitating transport to a dedicated facility(ies) with sufficient capacity to accommodate the accumulation of SNF for the time period of the extended storage (e.g., for 100 year extended decay storage, material would accumulate for 100 years before the first material is ready to move to the next phase) and a lifetime to allow the last SNF accepted to decay for the desired time period.

In contrast to the once-through strategy, there are more major components and operations with recycle strategies. Extended decay storage can be used in the same manner as in once-through strategies with the same potential benefits to planning and logistics for waste management. In addition, since there are more scientific and technological issues with recycle strategies, there is the benefit of providing the time needed for identifying, developing, and demonstrating the desired technologies. There can also be a significant benefit to processing UNF with lower radiation due to radioactive decay. However, radioactive decay can also change elements from ones that are easily recycled into ones that are more difficult, e.g., fissile ^{241}Pu decays to ^{241}Am. The usefulness of extended storage needs to be considered for the specific recycle conditions being proposed, and there are the additional costs and risks to be considered. However, there may be uncertainty about any detrimental effects from extended decay storage of UNF significantly beyond current experience that may for example make handling of the fuel more difficult because of physical degradation.

The effect of extended storage is comparable for all once-through strategies and limited recycle strategies due to the similarity in decay heat for the combined SNF and HLW. Interim storage allows time for decay of shorter-lived isotopes, both fission products and TRU that can have a beneficial impact by lowering the radiotoxicity and decay heat of the materials in storage, which would facilitate handling, any potential processing, and disposal. However, long-term radiotoxicity and decay heat that can be important to the disposal options are essentially unaffected by extended decay storage because the time frames are so much greater than the longest proposed extended decay storage. When extended decay storage is part of an implemented strategy, it is also important to recognize that there are costs and licensing issues to be considered.

For the first few decades after fuel discharge from a reactor, decay heat is dominated by short-lived fission products, and this could be addressed by using extended decay storage prior to disposal. However, the long-term decay heat, out to two thousand years or more, resulting from some of the actinide elements can only be addressed by recycle to keep these elements out of the wastes, aside from acceptable processing losses. As a result, once-through fuel cycles are limited in their ability to extend resources for deep geologic disposal due to the disposal of SNF, although cases with complete consumption of the fuel may be beneficial. Recycle of actinides can provide significant increase in fuel cycle performance.

There are specific instances in thermal reactor fuel cycle where the use of extended decay storage can allow radioactivity and decay heat to decrease, facilitating UNF reprocessing and recycle fuel fabrication. The longer decay time reduces the buildup of higher actinide elements with recycle by allowing the curium isotopes to decay and reduces the radiation and heating source terms during fuel handling. Additionally, in the fuel material ^{241}Pu decays to ^{241}Am in storage, which results in ^{238}Pu through transmutation and decay, instead of using ^{241}Pu in recycle fuel which fissions well, but also transmutes into ^{242}Pu and higher Am and Cm isotopes. However, the resulting loss of fissile ^{241}Pu and the neutron absorbing nature of ^{241}Am in the recycle fuel also needs to be considered. In order to have a self-sustaining critical system based on multi-recycle of TRU in thermal reactors, it is driven by the fission and excess neutrons from ^{235}U in natural uranium. This makes it necessary to add enriched uranium to the recycle fuel or operation at very low burnups in a thermal system with a very efficient neutron economy (e.g., a heavy-water system). This reduces fuel cycle performance if scarcity of uranium resources becomes constraining to nuclear utilization in the future. In that case, a nuclear system that could be used for breeding additional fuel would be attractive which are generally far less sensitive to ^{241}Pu decay in regards to both the importance as a fissile isotope and a gateway to higher actinide elements.

The decay heat of the fission products can be mitigated or eliminated with extended decay storage due to the relatively short term that they dominate decay heat, up to about 60 years, while their effect is essentially gone by about 300 years. Alternatively, an integrated fuel cycle could use separations to advantage to isolate high decay heat fission products from the remaining wastes, storing only those fission products for an extended period of time. The decay heat from the actinides persists for longer times, at least a thousand years, and extended decay storage would likely not be effective. If actinide decay heat causes difficulty with satisfying repository temperature limits, separation and recycle of the actinides or long-term storage (many hundreds of years or longer) are the only options to help improve use of repository space.

Decay heat is an operational and engineering issue in repository design, although the lower temperature limits for disposal in saturated clay increase the importance of the shorter-lived fission products, implying that extended decay storage could be an effective approach to increase repository performance. Whether the decay heat from the longer-lived actinide elements is important depends on the details of the disposal site, and if proved to be important, separation and recycle would be effective in increasing repository space utilization.

Impacts of Extended Storage on the Evaluation Criteria

The specific impact that extended decay storage might have on fuel cycle performance depends on the details of the fuel cycle objectives and associated design. This notwithstanding, some general observations can be made about the impact of extended storage for the Evaluation Criteria.

- Nuclear Waste Management Criterion: As noted above short term benefits might be derived by the use of extended storage due the ability to reduce heating rate in a repository setting. The long-term impact on the repository is however expected to be very small.
- Proliferation Risk Criterion: The fissile content and material attractiveness could be changed from the use of extended decay storage.
- Nuclear Material Security Risk Criterion: As with the proliferation risk criterion, the fissile content could be changed from the use of extended decay storage.
- Safety Criterion: Extended storage is not expected to impact the ability to deploy a fuel cycle option safely.
- Environmental Impact Criterion: Very little impact is expected from extended decay storage, even though the radiological exposure - total estimated worker dose per energy generated – would be lower.
- Resource Utilization Criterion: The resource utilization could be impacted for recycle thermal systems, when extended storage is used. Very little impact is expected for fuel cycle options dominated by fast spectrum systems.
- Development and Deployment Risk Criterion: Extended decay storage might alleviate handling issues in the fuel cycle, which would be beneficial for this criterion.
- Institutional Issues Criterion: Same as above for Development and Deployment Risk.
- Financial Risk and Economics Criterion: Impact is expected to be small. Some benefit is expected from the ease of material handling, but there is cost associated with the large storage that would be required.

Summary

In summary, extended decay storage (SNF/UNF, products, or wastes) may be a tool to improve overall system design efficiency, but it will not be a major driver in the overall system performance. Extended decay storage can:

- slowly lower radiation level by radioactive decay to potentially reduce worker exposure or shielding requirements, but the remaining radiation is sufficient to still require remote handling of the materials
- favorably affect recycle of some actinide elements such as curium, but may adversely affect recycle of other actinide elements such as plutonium
- slowly lower decay heat at the time of disposal for SNF, facilitating handling and emplacement, but is most effective for the HLW from recycle fuel cycles where most of the content is fission products with a relatively short radioactive half-life.