Introduction of the U.S. Nuclear Fuel Cycle Evaluation and Screening Study

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U.S. DEPARTMENT OF ENERGY

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Background

- **DOE chartered the Evaluation and Screening (E&S) Study in 2011 to strengthen the basis for DOE-NE R&D decisions**
  - Identify the potential for a nuclear fuel cycle to provide substantial improvements as compared to the current U.S. once-through fuel cycle, including both benefits and challenges for development
  - Identify promising fuel cycles with the potential to provide substantial improvements, not incremental or evolutionary changes
- **DOE-NE specified the Evaluation Criteria**
- **The study was directed to:**
  - Consider the complete nuclear fuel cycle system from mining to disposal
  - Develop a set of fuel cycles that is comprehensive with respect to potential fuel cycle performance
  - Develop appropriate evaluation metrics for the criteria
  - Explore the impacts of different criteria weighting factors that reflect the range of possible policy guidance and illustrate the effects of specific policy choices
- **The Evaluation and Screening Team (EST) was established for the E&S study**

Criteria and Evaluation Metrics

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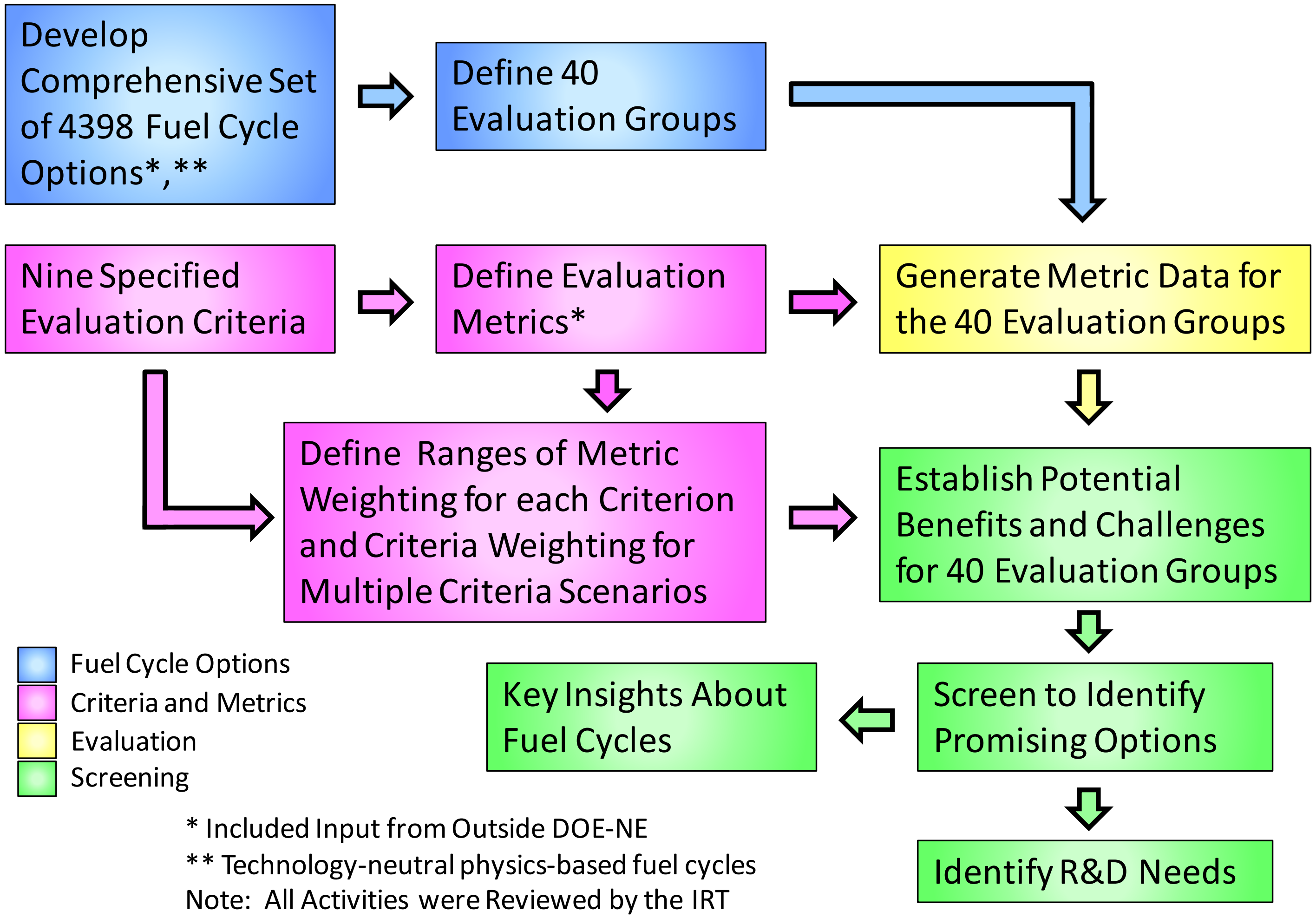
"Benefit" Criteria	
Nuclear Waste Management	Mass of SNF+HLW disposed per energy generated
	Activity of SNF+HLW (@100 years) per energy generated
	Activity of SNF+HLW (@100,000 years) per energy generated
	Mass of DU+RU+RTh disposed per energy generated
	Volume of LLW per energy generated
Proliferation Risk	Material attractiveness – normal operating conditions
Nuclear Material Security Risk	Material attractiveness – normal operating conditions
	Activity of SNF+HLW (@10 years) per energy generated
Safety	Challenges of addressing safety hazards
	Safety of the deployed system
Environmental Impact	Land use per energy generated
	Water use per energy generated
	Radiological exposure - total estimated worker dose per energy generated
	Carbon emission - CO_2 released per energy generated
Resource Utilization	Natural Uranium required per energy generated
	Natural Thorium required per energy generated
"Challenge" Criteria	
Development and Deployment Risk	Development time
	Development cost
	Deployment cost from prototypic validation to FOAK commercial
	Compatibility with the existing infrastructure
	Existence of regulations for the fuel cycle and familiarity with licensing
	Existence of market incentives and/or barriers to commercial implementation of fuel cycle processes
Institutional Issues	Compatibility with the existing infrastructure
	Existence of regulations for the fuel cycle and familiarity with licensing
	Existence of market incentives and/or barriers to commercial implementation
Financial Risk and Economics	Levelized Cost of Electricity at Equilibrium

- **High-level criteria are defined in DOE's Charter for E&S Study**
- **E&S Team developed evaluation metrics, coordinated with input from DOE, industry, universities, and others through collaborations, meetings, and iterations**
- **26 metrics are grouped into "Benefit" and "Challenge" Criteria**

Structure of E&S Study

SA&I SYSTEMS ANALYSIS AND INTEGRATION



- **EST identified 4398 fuel cycle options, which were reduced ~640 compressive fuel cycle option groups, and reduced them again into 40 Evaluation Groups (EGs)**
- **DOE-NE provided nine evaluation criteria**
- **EST defined 26 fuel cycle evaluation metrics**
- **EST calculated metric data of 40 Evaluation Groups (EGs)**
- **By comparing fuel cycle metrics of 40 EGs, EST identified promising fuel cycles**

Terminology

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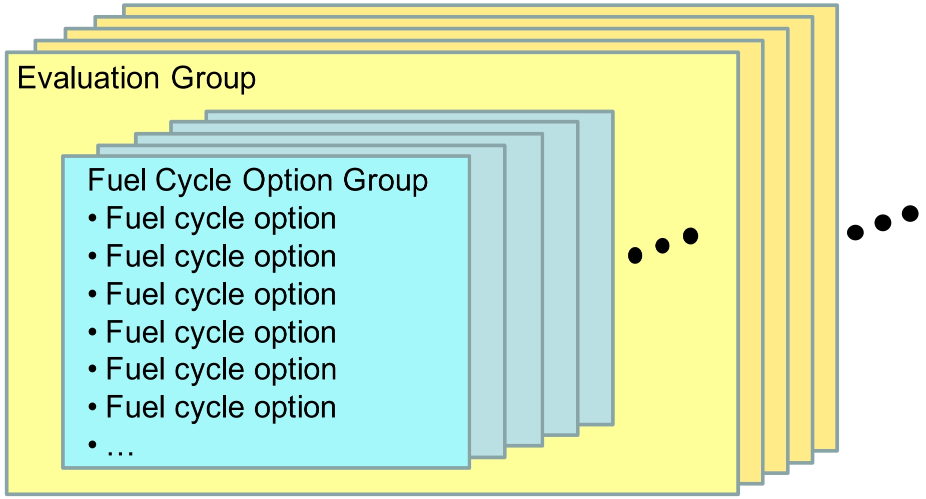
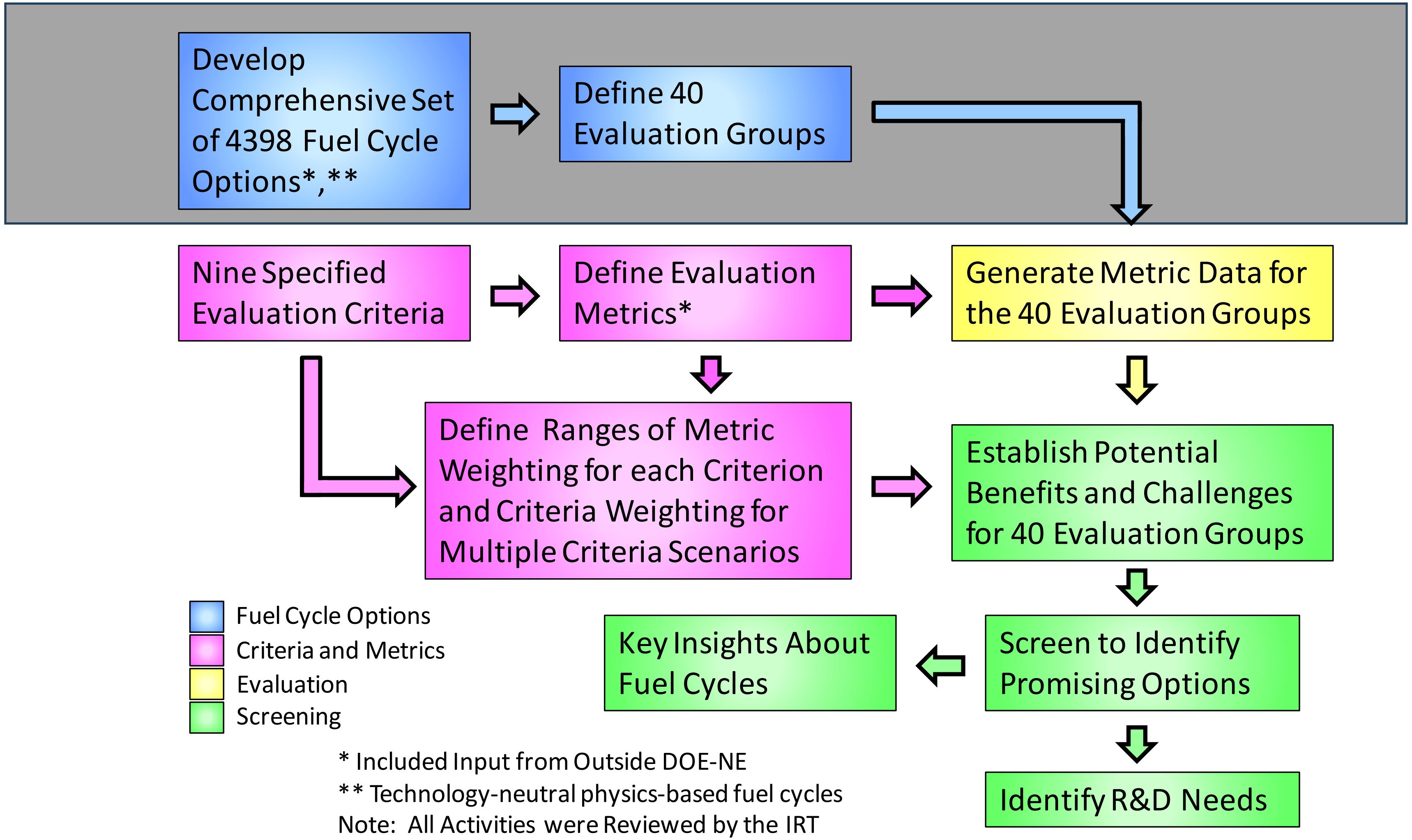
- **Nuclear fuel cycle**
  - Complete nuclear energy systems from mining to disposal (e.g., once-through, recycle, limited-recycle)
- **Fuel cycle options (~4,400)**
  - A Nuclear Fuel Cycle with specific technologies for enrichment (if needed), fuel fabrication, reprocessing (if needed), and used fuel storage or disposal (e.g., once-through PWR with 5% LEU fuel).
- **Comprehensive fuel cycle option groups (~640)**
  - Collection of Nuclear Fuel Cycle Options at the functional level with similar fundamental physics principles and fuel cycle characteristics (e.g., once-through thermal critical reactors with enriched uranium fuel)
- **Evaluation groups (~40)**
  - Collection of Nuclear Fuel Cycle Groups based on similarities in expected physics-based performance (e.g., once-through with enriched uranium fuel and similar uranium utilization)



Evaluation Groups



* Included Input from Outside DOE-NE
** Technology-neutral physics-based fuel cycles
Note: All Activities were Reviewed by the IRT

Comprehensive Fuel Cycle Option Groups

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- **EST utilized discriminators for grouping ~4,400 fuel cycle options into comprehensive fuel cycle option groups.**
  1. Recycling: Once-through vs. recycle
  2. Reactivity: Critical or sub-critical systems
  3. Neutron spectrum: Thermal, Intermediate, or Fast
  4. Feed fuel material: Uranium or Thorium
  5. Recycling Element: U, Pu, MA, TRU, or FP
  6. Need for enrichment: Yes or no (not considered assay range)
  7. Recycling Stages: a combination of critical and subcritical systems
- **638 comprehensive fuel cycle option groups**
  - Once-through fuel cycle options: 30 -> 20
  - Limited recycling fuel cycle options: 336 -> 308
  - Continuous recycling fuel cycle options: 4032 -> 308

Evaluation Groups

- **EST reduced the comprehensive fuel cycle option groups further, using two rules**
  - Rule 1: group fuel cycle option groups if the expected physics-based performance is similar
    - Ignore MA-only and FP-only recycles
    - Ignore U-only and Th-only recycling
    - Ignore the difference between homogeneous and heterogeneous recycling options
    - Combine intermediate spectrum systems into a fast spectrum
    - Delete sub-critical/sub-critical two (or multiple) stage systems
  - Rule 2: group the fuel cycle performance characteristics that are similar
    - Front-end fuel cycle guidance: Uranium (thorium) utilization range: <3%, 3-30%, > 30%
    - Back-end fuel cycle guidance: Recycling materials: SNF, SNF+HLW, HLW (Once-through, limited, continuous)
- **638 fuel cycle option groups were reduced to 40 groups, which is a sufficient groups for evaluation and defined as EGs**

40 Evaluation Groups

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Evaluation Group	Short Description Indicative of Fuel Cycles in the Evaluation Group (Detailed Description of Each Evaluation Group is in Appendix B)
Once-through	
EG01	Once-through using enriched-U fuel in thermal critical reactors
EG02	Once-through using enriched-U fuel to high burnup in thermal or fast critical reactors
EG03	Once-through using natural-U fuel in thermal critical reactors
EG04	Once-through using natural-U fuel to very high burnup in fast critical reactors
EG05	Once-through using enriched-U/Th fuel in thermal or fast critical reactors
EG06	Once-through using Th fuel to very high burnup in thermal EDS
EG07	Once-through using natural-U fuel to very high burnup in thermal or fast EDS
EG08	Once-through using Th fuel to very high burnup in fast EDS
Limited Recycle	
EG09	Limited recycle of U/TRU with new natural-U fuel to very high burnup in fast critical reactors
EG10	Limited recycle of ^{233}U/Th with new Th fuel in fast and/or thermal critical reactors
EG11	Limited recycle of ^{233}U/Th with new enriched-U/Th fuel in fast or thermal critical reactors
EG12	Limited recycle of U/Pu with new natural-U fuel in fast and/or thermal critical reactors
EG13	Limited recycle of U/Pu with new enriched-U fuel in thermal critical reactors
EG14	Limited recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors
EG15	Limited recycle of U/Pu with new enriched-U fuel in both fast and thermal critical reactors
EG16	Limited recycle of U/Pu with new enriched-U fuel in thermal critical reactors and fast EDS
EG17	Limited recycle of Pu/Th with new enriched-U/Th fuel in thermal critical reactors
EG18	Limited recycle of ^{233}U/Th with new enriched-U/Th fuel in thermal critical reactors

Continuous Recycle	
EG19	Continuous recycle of U/Pu with new natural-U fuel in thermal critical reactors
EG20	Continuous recycle of U/TRU with new natural-U fuel in thermal critical reactors
EG21	Continuous recycle of U/Pu with new enriched-U fuel in thermal critical reactors
EG22	Continuous recycle of U/TRU with new enriched-U fuel in thermal critical reactors
EG23	Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors
EG24	Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors
EG25	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in thermal critical reactors
EG26	Continuous recycle of ^{233}U/Th with new Th fuel in thermal critical reactors
EG27	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in fast critical reactors
EG28	Continuous recycle of ^{233}U/Th with new Th fuel in fast critical reactors
EG29	Continuous recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors
EG30	Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors
EG31	Continuous recycle of U/Pu with new enriched-U fuel in both fast and thermal critical reactors
EG32	Continuous recycle of U/TRU with new enriched-U fuel in both fast and thermal critical reactors
EG33	Continuous recycle of U/Pu with new natural-U fuel in both fast EDS and thermal critical reactors
EG34	Continuous recycle of U/TRU with new natural-U fuel in both fast EDS and thermal critical reactors
EG35	Continuous recycle of U/Pu with new enriched-U fuel in both thermal critical reactors and fast EDS
EG36	Continuous recycle of U/TRU with new enriched-U fuel in both thermal critical reactors and fast EDS
EG37	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in both fast and thermal critical reactors
EG38	Continuous recycle of ^{233}U/Th with new Th fuel in both fast and thermal critical reactors
EG39	Continuous recycle of ^{233}U/Th with new enriched-U fuel in both thermal critical reactors and fast EDS
EG40	Continuous recycle of ^{233}U/Th with new Th fuel in fast EDS and thermal critical reactors

- **EG02 – high burnup thermal reactor with HALEU fuel**
- **EG13 – MOX concepts considered by France and Japan**
- **EG 23/24 – Conventional recycling with fast reactors**

Example EGs

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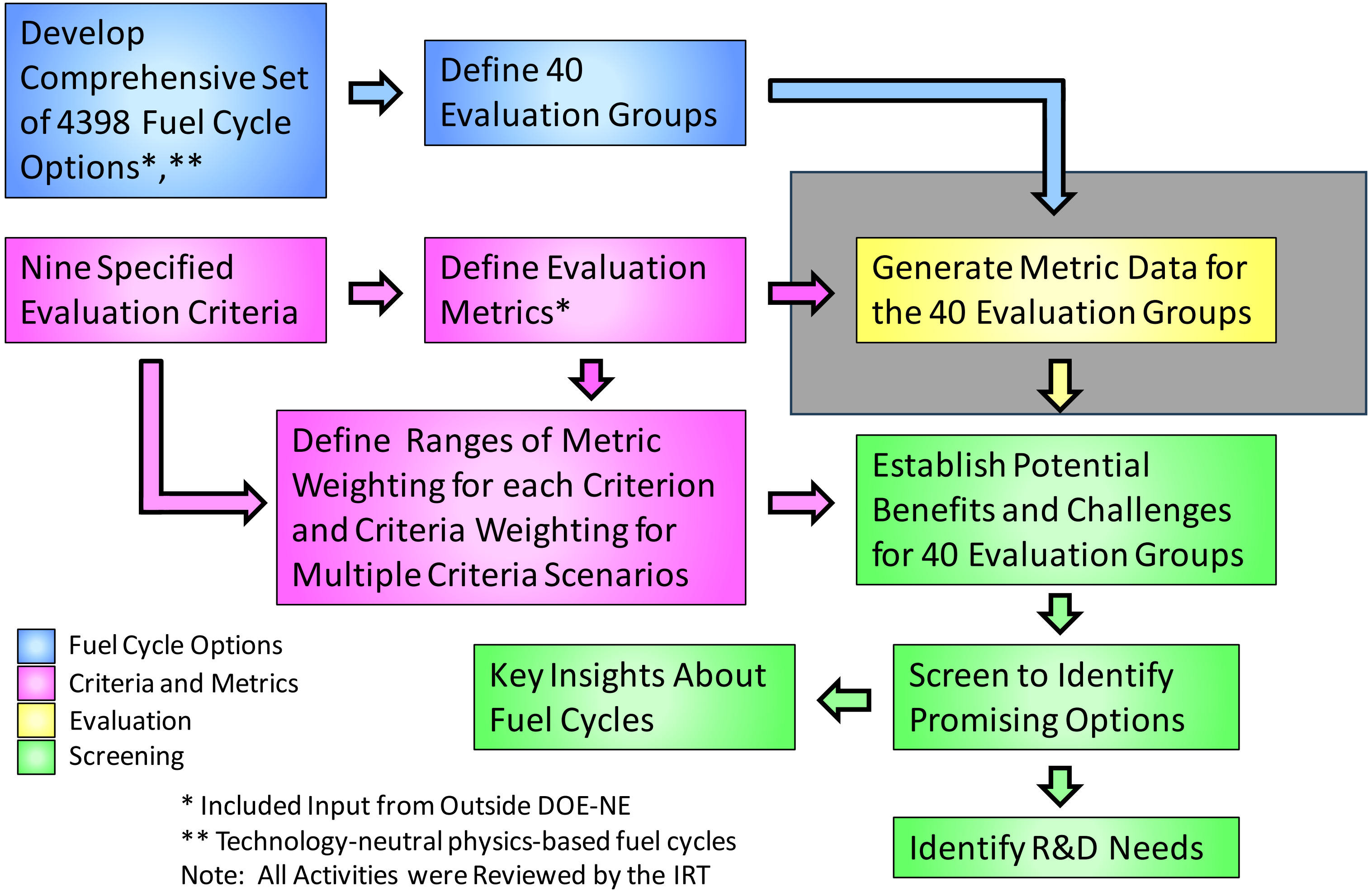
Table B9. Grouping and Analysis Examples for Once-Through Fuel Cycles.

	Included Fuel Cycle Option Groups From Table B6	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG01	OT-C-T-U-Y	Critical	Thermal	U	-	Yes	Natural U feed Enriched to <5 w/o U-235 Critical reactor Thermal spectrum Resource utilization ~0.6% **Basis for comparison**
Analysis Example For EG01	Option description			Once-Through: PWR LEU base case (50 GWd/t burnup)			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU; --; discharged fuel (DF))			
Evaluation group EG02	OT-C-T-U-Y	Critical	Thermal	U	-	Yes	Natural U feed Enrichments in range 5-20 w/o U-235 Critical reactors and EDS Thermal or fast spectra Resource utilization up to 3%
	OT-C-F-U-Y	Critical	Fast	U	-	Yes	
	OT-S-T-U-Y	SubCrit.	Thermal	U	-	Yes	
	OT-S-F-U-Y	SubCrit.	Fast	U	-	Yes	
Analysis Example For EG02	Option description			Once-Through: HTGR (graphite-moderated, He-cooled)			
	Reactor ([Startup];Driver; Blanket; Waste)			HTGR([--]; LEU; --; DF)			
Evaluation group EG03	OT-C-T-U-N	Critical	Thermal	U		No	Natural U feed No Enrichment Critical reactors Thermal spectra Resource utilization up to 3%
Analysis Example For EG03	Option description			Once-Through: HWR with NU			
	Reactor ([Startup];Driver; Blanket; Waste)			HWR([--]; NU; --; DF)			

- **Uranium utilization of Fuel cycle option groups in EG02 is less than 3% regardless of neutron spectrum (fast or thermal) and reactivity (critical or sub-critical) with LEU fuel**
- **HTGR with LEU fuel was considered as the Analysis Example of EG02**

Calculation of Metric Data of 40 EGs



* Included Input from Outside DOE-NE

** Technology-neutral physics-based fuel cycles

Note: All Activities were Reviewed by the IRT

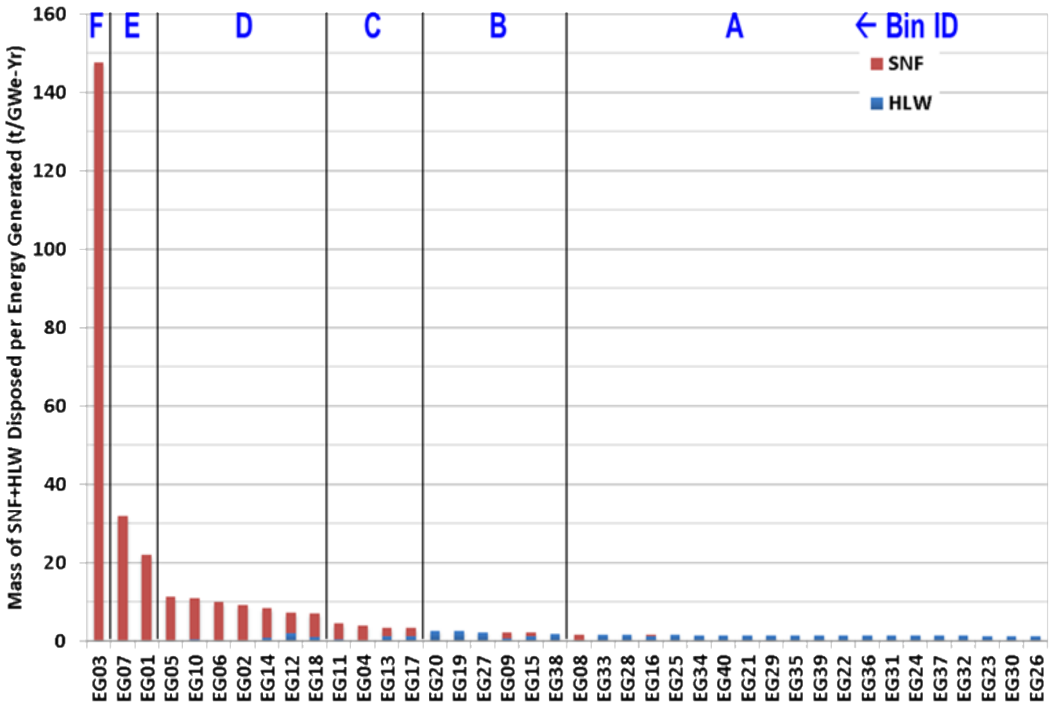
Generation Metric Data of 40 EGs

- **EST pick Analysis Example fuel cycle option in each EG**
- **The fuel cycle performance data of each EG were calculated using the Analysis Example (AE) at the Equilibrium State**
- **Since each EG consists of multiple fuel cycle option groups and each fuel cycle option group consists of multiple fuel cycle options (technologies), two tactics were adopted.**
  - Technology neutral metrics – renormalization of mass flow data using the same thermal efficiency
  - Binned metrics
- **Calculated physics data are stored using the Fuel Cycle Data Package (FCDP) and populated through the Fuel Cycle Catalog.**

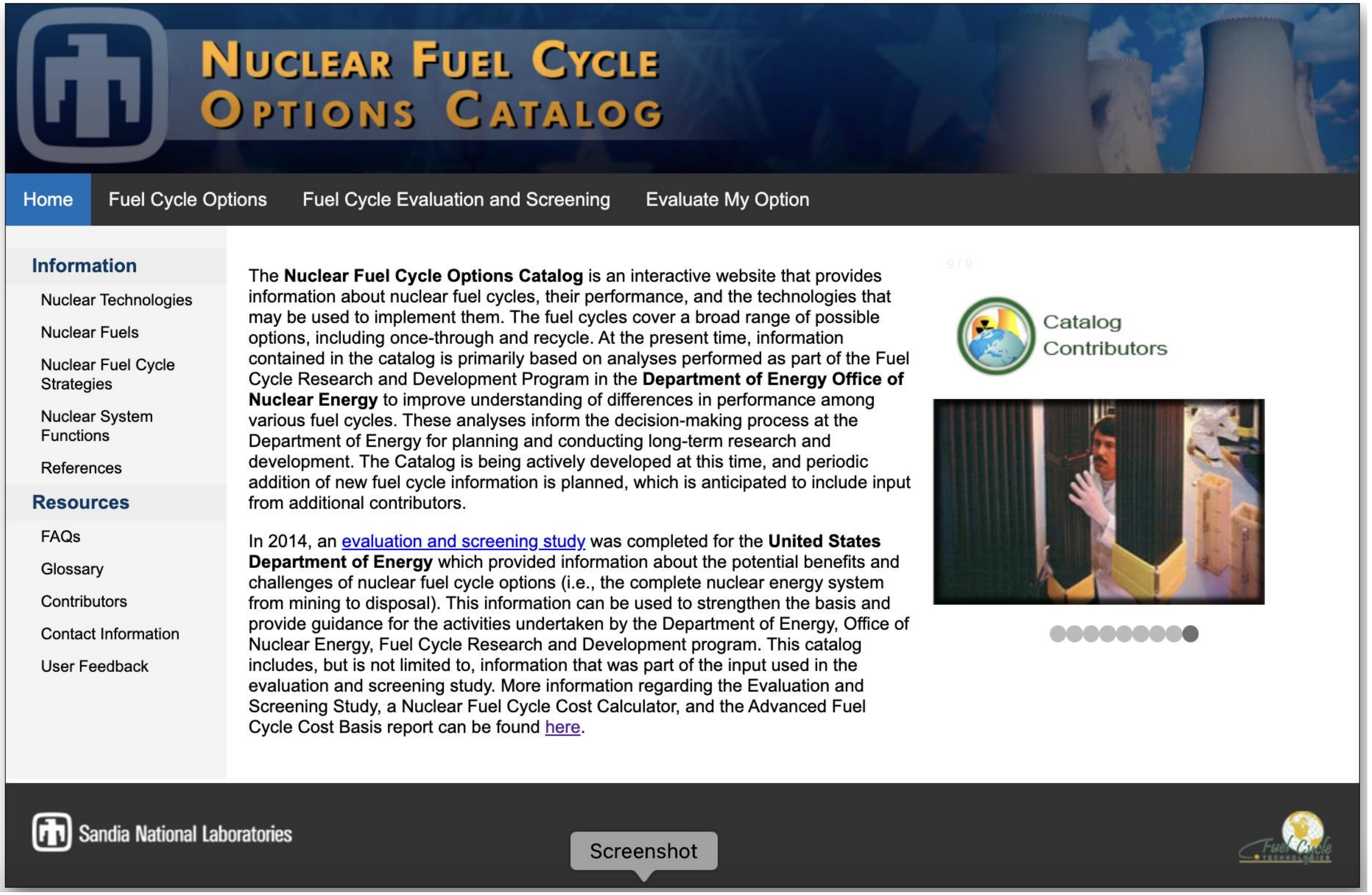
Binned Metric Data – SNF+HLW Mass

Table C-1.1. 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



Fuel Cycle Data Repository


NUCLEAR FUEL CYCLE OPTIONS CATALOG

Home | Fuel Cycle Options | Fuel Cycle Evaluation and Screening | Evaluate My Option

Information
- Nuclear Technologies
- Nuclear Fuels
- Nuclear Fuel Cycle Strategies
- Nuclear System Functions
- References

Resources
- FAQs
- Glossary
- Contributors
- Contact Information
- User Feedback

The **Nuclear Fuel Cycle Options Catalog** is an interactive website that provides information about nuclear fuel cycles, their performance, and the technologies that may be used to implement them. The fuel cycles cover a broad range of possible options, including once-through and recycle. At the present time, information contained in the catalog is primarily based on analyses performed as part of the Fuel Cycle Research and Development Program in the **Department of Energy Office of Nuclear Energy** to improve understanding of differences in performance among various fuel cycles. These analyses inform the decision-making process at the Department of Energy for planning and conducting long-term research and development. The Catalog is being actively developed at this time, and periodic addition of new fuel cycle information is planned, which is anticipated to include input from additional contributors.

In 2014, an evaluation and screening study was completed for the **United States Department of Energy** which provided information about the potential benefits and challenges of nuclear fuel cycle options (i.e., the complete nuclear energy system from mining to disposal). This information can be used to strengthen the basis and provide guidance for the activities undertaken by the Department of Energy, Office of Nuclear Energy, Fuel Cycle Research and Development program. This catalog includes, but is not limited to, information that was part of the input used in the evaluation and screening study. More information regarding the Evaluation and Screening Study, a Nuclear Fuel Cycle Cost Calculator, and the Advanced Fuel Cycle Cost Basis report can be found here.

Catalog Contributors

Sandia National Laboratories

Screenshot

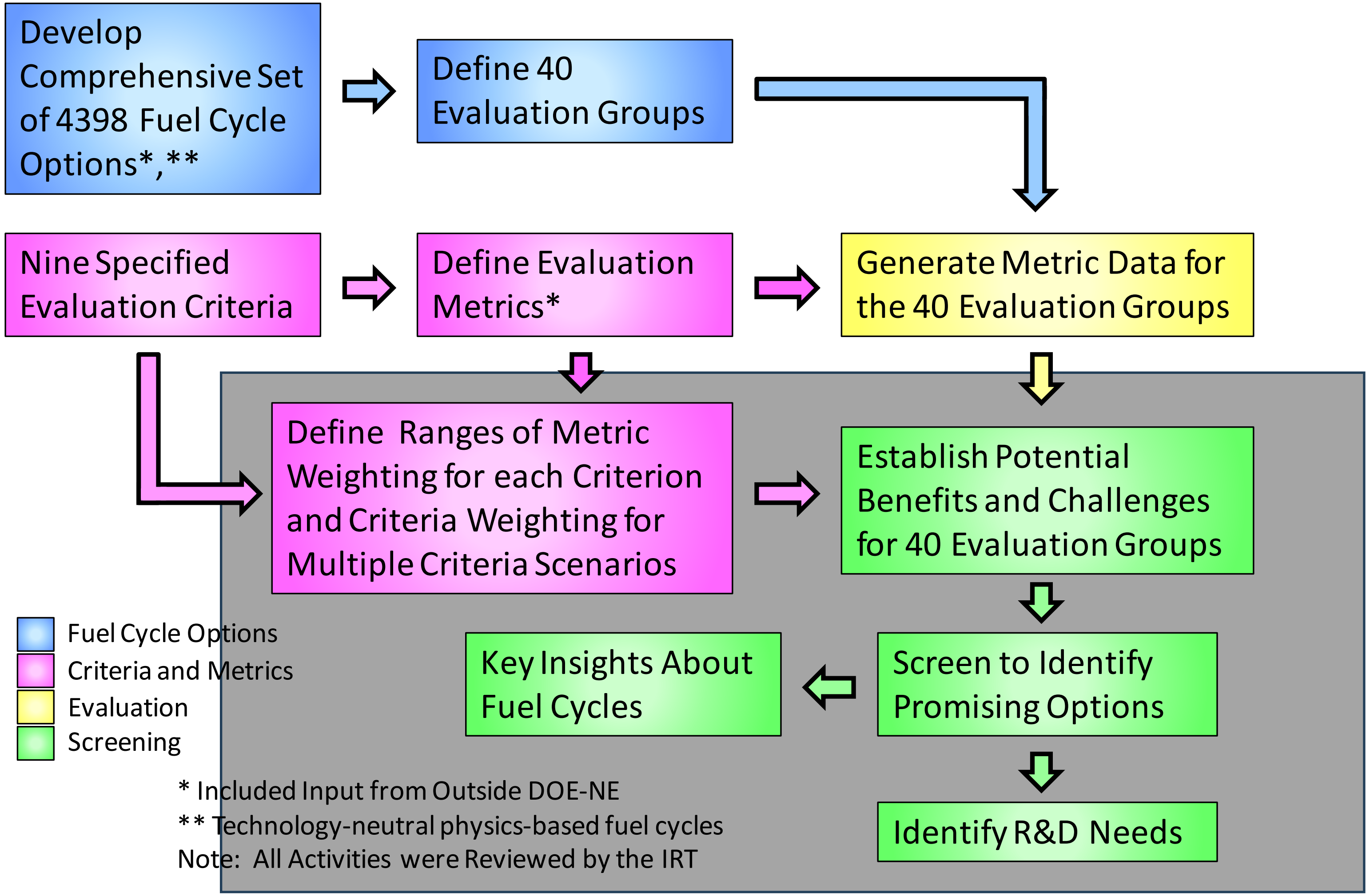
https://sai.inl.gov/

Completion of Fuel Cycle Data Package System Datasheets for 2013 Evaluation and Screening

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Fuel Cycle Options Campaign
T. K. Kim, E. A. Hoffman, and T. A. Taiwo
May 30, 2013
ANL-FCT-333
FCRD-FCO-2013-000165

Screening Study



Screening Study using Scenarios

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

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

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

- **A screening study was conducted with eleven scenarios with different weighting factors.**

Scenario #2 – Emphasize Waste Management

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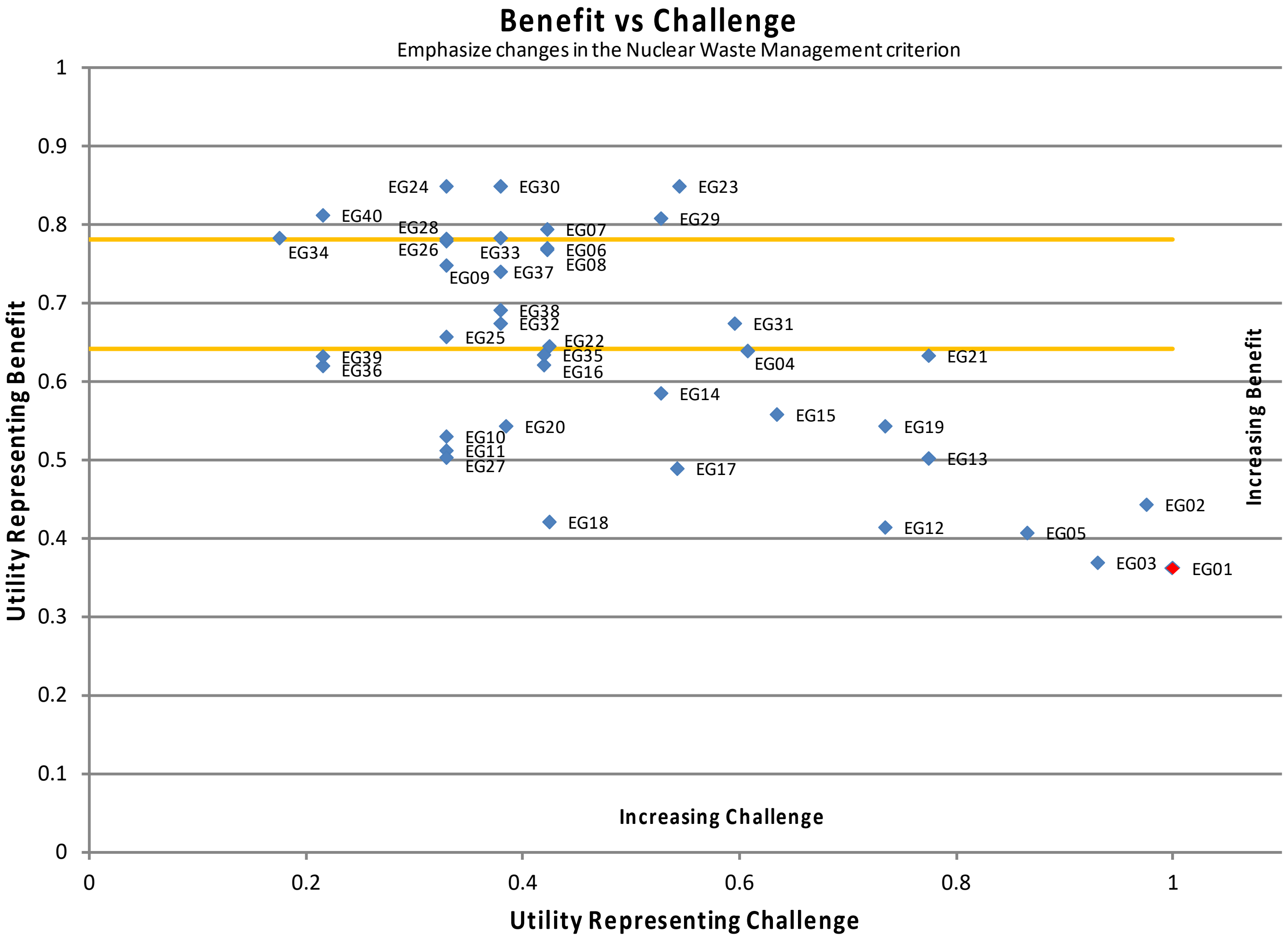

- **EG01 does not have any challenging issues, but it has the lowest benefit**
- **EG23, EG24, and EG30 give the best benefit in waste management**

Performance of Promising Fuel Cycles

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Table 6. Summary of Metrics for the Benefit Criteria for the Best-Performing Evaluation Groups.

	Once-through	Continuous Recycle		
Fuel Cycle Option	**EG01 – Current U.S. Fuel Cycle**	**EG23 – U/Pu Recycle, Fast Systems**	**EG24 – U/TRU Recycle, Fast Systems**	**EG30 – U/TRU Recycle, Fast and Thermal Systems**
Nuclear Waste Management Criterion				
Mass of SNF+HLW, t/GWe-yr	12-36	< 1.65	< 1.65	< 1.65
Activity @100 years, MCi/GWe-yr	1.05-1.60	0.67-1.05	0.67-1.05	0.67-1.05
Activity @100,000 years, MCi/GWe-yr	0.001-0.0023	0.0005-0.001	0.0005-0.001	0.0005-0.001
Mass of DU+RU+RTh, t/GWe-yr	120-200	<1	<1	<1
Volume of LLW, m^3/GWe-yr	252-634	252-634	252-634	252-634
Proliferation Risk Criterion				
Material attractiveness – normal operating conditions	Unattractive	Unattractive	Unattractive	Unattractive
Nuclear Material Security Risk Criterion				
Material attractiveness – normal operating conditions	Unattractive	Unattractive	Unattractive	Unattractive
Activity @10 years per energy generated	Highly radioactive	Highly radioactive	Highly radioactive	Highly radioactive
Safety Criterion				
Challenges of addressing safety hazards	Reference	Similar	Similar	Similar
Safety of the deployed system	Yes	Yes	Yes	Yes
Environmental Impact Criterion				
Land use, km^2/GWe-yr	0.1 - 0.2	< 0.1	< 0.1	< 0.1
Water use, ML/GWe-yr	15000 - 30000	15000-30000	15000-30000	15000-30000
CO_2 emission, kt/GWe-yr	30-60	< 30	< 30	< 30
Radiological exposure, person-Sv/GWe-yr	0.5 - 5	0.5 - 5	0.5 - 5	0.5 - 5
Resource Utilization Criterion				
Uranium resources, t/GWe-yr	> 145	< 3.8	< 3.8	< 3.8

- **The most promising fuel cycle is "Continuous recycling of U/Pu or U/TRU with new natural uranium fuel in fast or along with thermal critical reactors."**
- **Compared to the current U.S. fuel cycle, the performance benefits of the most promising fuel cycles are**
  - Greater than a factor of 10 reduction in the amount of high-level waste disposal.
  - Greater than a factor of 1,000 reduction in the amount of uranium disposal.
  - Greater than a factor of 100 improvement in uranium utilization.

Conclusions

- **Systems Analysis and Integration (aka, Fuel Cycle Options) conducted the Nuclear Fuel Cycle Evaluation and Screening study to identify promising fuel cycles in the United States**
  - DOE-NE specified the Evaluation Criteria
  - The Evaluation and Screening Team (EST) developed evaluation metrics and procedures
  - The E&S study results are available at the Systems Analysis and Integration (SA&I) campaign (https://sai.inl.gov/)
- **The E&S study concluded that the most promising fuel cycle is ”Continuous recycling of U/Pu or U/TRU with new natural uranium fuel in fast or along with thermal critical reactors.”**