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Fuel Cycle Research and Development

Approach For Development Of Sets Of Fuel Cycle Options And Groups

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Presentation Outline

- **Objective**
- **Fuel Cycle Options and Groups**
- **Closing Remarks**

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Presentations - Objective

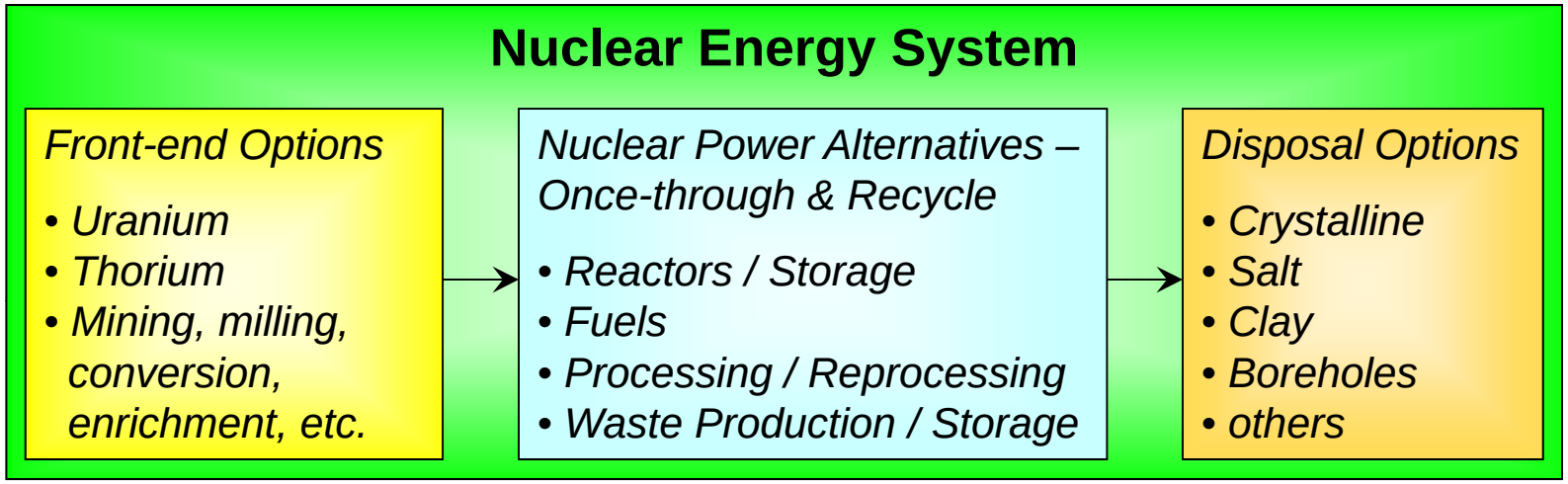
1. Purpose and Objectives of the 2013 Evaluation and Screening Effort
   - Background
   - Context
   - Overall Process
2. Fuel Cycle Characteristics Affecting Performance
3. **Approach for Development of Sets of Fuel Cycle Options and Groups**
4. Examples of Fuel Cycle Options
5. Process for Submitting Fuel Cycle Concepts
   - Role of Participants
   - Requested information
   - Steps of the Process

Approach in Preparing for FY2013 Screening Effort

- **Based on new Charter approved by NE-1**
  - High-level criteria for evaluating improvement in fuel cycle performance
  - Metrics to describe and characterize performance of fuel cycle options relative to the criteria
  - A comprehensive list of fuel cycle options
  - An approach to group fuel cycle options with similar characteristics and expected fuel cycle performance

- **The main objective is that fuel cycle options are "comprehensive" in terms of fuel cycle characteristics that affect performance with respect to the high-level criteria.**

Nuclear Energy Systems



- **A Nuclear Energy System (fuel cycle option) includes everything**
  - From mining through disposal, and everything in between
- **Each part of the Nuclear Energy System has a list of options**
- **A specific "Fuel Cycle Option" or "Nuclear Energy System" consists of a combination of elements from each of the three boxes**

Terminology Issues

- **As described on the previous slide, a "Nuclear Energy System" (NES) is a combination of:**
  - Front End Options, e.g.,uranium
  - Nuclear Power Alternatives, e.g., reactors, externally driven systems
  - Disposal Options, e.g., boreholes
- **The Nuclear Power Alternatives component of each NES is where incoming materials are changed as a result of irradiation**
- **Recognize that the terminology "Fuel Cycle Option" is not unique and may be associated with part or all of the Nuclear Energy System.**

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What Does "Comprehensive in Terms of Characteristics Affecting Performance" Mean?

- **As noted in the previous slides, a "Nuclear Energy System" (NES)/"Fuel Cycle Option" consists of a combination of elements, from the Front End, Nuclear Power Alternatives, and Disposal Options.**
  - The focus is on "Nuclear Power Alternatives" (the "blue box")
- **The planned approach intends to make the eventual evaluation and screening tractable, while still covering the full spectrum of performance of fuel cycle options by focusing on fundamental physics in defining options, e.g.:**
  - Critical or Sub-Critical
  - Spectrum: Thermal; Intermediate; Fast
  - Incoming Fuel Material: U; U/Th; Th
  - Is Enrichment Required?: No; Yes

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The Fuel Cycle Options List

- **The development of the list of Fuel Cycle Options uses three focus areas to create a list comprehensive in terms of potential nuclear fuel cycle performance that addresses the high-level evaluation criteria:**
  - Developed by internationally recognized subject matter experts from the DOE national laboratories – **Basic Principles**
  - Thorough examination of historically available information is being performed – **Past Studies**
  - Outreach efforts to experts outside the FCT program (universities, industry, national laboratories, others) to give them an opportunity to contribute to the list – **Current Concepts**
- **How does one ensure that a list of fuel cycle options is comprehensive for the evaluation and screening?**
  - Start with the nuclear physics that determines how incoming materials are used and what products they will make

Approach for Developing Fuel Cycle Options List – Basic Principles

- **Fuel cycle performance is basically determined by the materials going in, how they are used, and the materials coming out**
  - All aspects that affect the content and disposition of all materials (fuel, structure, equipment, etc.) are considered
- **Characteristics that affect performance include:**
  - Once-through or Recycle (Limited or Continuous)
  - Characteristics of the irradiation device (reactor or EDS) and choices for the materials used in irradiation determine the product materials
  - Neutron Spectrum (typically categorized as thermal, intermediate, fast)
  - Need for uranium enrichment depends on the fuel materials, neutron spectrum, and core design
  - Fuel storage duration and processing
  - Content and characteristics of materials sent to geologic disposal and the disposal environment

Approach for Developing Fuel Cycle Options List – Past Studies

- **Studies evaluating the performance of broad ranges of fuel cycle options have been performed in the past**
  - Not necessarily comprehensive with respect to the criteria that reflect fuel cycle performance
- **The options considered in those studies will be reviewed and included as appropriate:**
  - All fuel cycle options included in previous broad-scope studies, e.g., INFCE and NASAP, and currently-proposed international fuel cycle approaches
  - Fuel cycle options from earlier FCRD (and predecessor DOE-NE) programs

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Example of Past Studies

Study	Objective and Outcome
Nonproliferation Alternative Systems Assessment Program (NASAP) [DOE-1] 1980	This U.S. study assessed the relationship between the civilian nuclear power and research program and the proliferation of nuclear weapons, with the intent to provide recommendations for the development and possible deployment of "more proliferation-resistant" civilian nuclear power systems. The study focused on the potential proliferation implications of nuclear power systems.
International Nuclear Fuel Cycle Evaluation (INFCE) [IAEA-1] 1980	The was an international technical study of fuel cycle cycles that can be used to meet the world's energy requirements and at the same time minimizing the danger of proliferation of nuclear weapons. There was no direct comparison of the systems and their performance relative to each other or a reference.
Gen IV Nuclear Energy Systems [DOE-2] 2002	This was an international effort designed to develop future generation nuclear energy systems that can be deployed by 2030, while satisfactorily addressing nuclear safety, waste, nonproliferation, and public perception concerns. A detailed evaluation of nuclear systems was performed to determine which of the systems were worthy of future R&D to support deployment. The effort was however focused more on advanced nuclear energy systems, than the overall fuel cycle, even though fuel cycle metrics were used in the assessment. Six systems were considered worthy of future investigations; VHTR, SFR, SCWR, GFR, LFR, and MSR.

Approach for Developing Fuel Cycle Options List – Current Concepts

- **All submitted concepts are planned to be explicitly included**
  - To promote the inclusive aspect of the fuel cycle options being considered
  - To avoid the need to explain why specific options might not have been in the list when one or more parties may be actively pursuing such options, i.e., the options list is complete with regards to the priorities of such interested parties

Grouping the List of Options to Make the Evaluation & Screening Tractable

- **An approach to group specific fuel cycle options with similar fuel cycle performance such that:**
  - There is sufficient division of the range of fuel cycle performance to allow a meaningful discrimination of expected performance from one fuel cycle group to the next with respect to the evaluation metrics
  - The goal is that a single option can be representative of the performance of the fuel cycle options in the group with an accuracy sufficient to allow the screening of the most promising fuel cycle group(s)
  - The total number of groups is such that the evaluation and screening process is tractable

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Example of How to Make Process Tractable

- **For example, the following systems, although different on the surface, in terms of fuel cycle performance are essentially equivalent**
- **3-Stage system: LWR / LWR / Fast Reactor TRU Burner, continuous recycle**
  - 1st Stage – LWR using LEU-UOX fuel
  - 2nd Stage – LWRs using U/Pu MOX, U/Pu from 1st Stage
  - 3rd Stage – Fast reactor TRU burner, MA from 1st Stage, U/TRU from 2nd and 3rd Stages
- **2-Stage system: LWR / Fast Reactor TRU Burner, continuous recycle**
  - 1st Stage – LWR using both LEU-UOX fuel and U/Pu MOX with U/Pu from LEU-UOX fuel
  - 2nd Stage – Fast reactor TRU burner, U/TRU from 1st and 2nd Stages
- **Similar arguments will be employed to manage the number of explicit options/groups that must be considered in the evaluation and screening**

Preliminary Grouping of Nuclear Power Alternatives: Once-Through

Once-Through Hierarchy:

- Critical or Sub-Critical
- Spectrum: Thermal; Intermediate; Fast
- Incoming Fuel Material: U; U/Th; Th
- Enrichment Required?: No; Yes

Example: Once-Through Uranium Incoming Fuel/Critical

Group	Example Options	Descriptor
Spectrum: Thermal **Enrichment:** No	HWR with NU	HWR(NU;;)→DF
	Graphite-moderated, CO_2-cooled	TR(NU;;)→DF
Spectrum: Thermal **Enrichment:** Yes	LWR LEU reference case (up to 50 GWth-d/t, 4.3% LEU)	LWR(LEU;;)→DF
	LWR LEU low burnup case (30 GWth-d/t, 3% LEU)	LWR(LEU;;)→DF
	LWR LEU intermediate (e.g., 75 GWth-d/t, 6% LEU)	LWR(LEU;;)→DF
	LWR LEU high-burnup (e.g., up to 100 GWth-d/t, 8% LEU)	LWR(LEU;;)→DF
	LWR LEU very high-burnup (e.g., >100 GWth-d/t, >8% LEU)	LWR(LEU;;)→DF
	HWR with slightly enriched uranium	HWR(LEU;;)→DF
	HWR LEU high-burnup (e.g., >20 GWth-d/t)	HWR(LEU;;)→DF
	HW-moderated LW-cooled with slightly enriched uranium	HWLW (LEU;;)→DF
	HTGR (graphite-moderated, He-cooled)	HTGR(LEU;;)→DF
	Graphite-moderated, water cooled	TR(LEU;;) → DF
	Liquid-salt cooled	TR(LEU;;) → DF
	Heavy water moderated, organic liquid-cooled thermal reactor	TR(LEU;;)→DF
	Graphite-moderated, CO_2-cooled	TR(LEU;;)→DF
	VHTR (graphite-moderated, He-cooled)	VHTR(LEU;;)→DF

Example: Once-Through Uranium Incoming Fuel/Critical (Cont'd)

Group	Example Options	Descriptor
Spectrum: Intermediate **Enrichment:** No	**No options possible**	
Spectrum: Intermediate **Enrichment:** Yes	Supercritical-water cooled LEU	SCWR(LEU;;)→DF
Spectrum: Fast **Enrichment:** No*	Breed-and-Burn	
Spectrum: Fast **Enrichment:** Yes	Molten Salt Reactor LEU	MSR(LEU;;)→DF
	Sodium-cooled fast reactor LEU	SFR(LEU;;)→DF
	Gas-cooled fast reactor LEU	GFR(LEU;;)→DF
	Lead-cooled fast reactor LEU	LFR(LEU;;)→DF
	FR liquid-salt cooled LEU	FR(LEU;;)→DF

* Enrichment required for startup, not at "equilibrium"

Preliminary Grouping of Nuclear Power Alternatives: Single-Stage Recycle

Single-Stage Recycle Hierarchy:

- Limited or Continuous
- Critical or Sub-Critical
- Spectrum: Thermal; Intermediate; Fast
- Incoming Fuel Material: U; Th; U/Th
- Recycled Elements: U; Pu; MA; All TRU; Th; Fission Products
- Enrichment Required?: No; Yes

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Example: Single-Stage Recycle

Limited or Continuous	Reactivity	Neutron Spectrum	Incoming Feed Fuel Material	Recycled Elements	Requires Enrichment?	Example Fuel Cycle Option
Continuous	Critical	Fast	U	TRU,RU	No	SFR(TRU/U*),LFR,GCFR
[redacted]						
Limited	Critical	Fast	U	TRU/RU and some FP	No	SFR(TRU/U*,FP)
[redacted]						
Continuous	Critical	Thermal	U	TRU,RU	Yes	PWR(CORAIL)
[redacted]						
Continuous	Critical	Thermal	Th	U,Th	No*	MSR(U-233/Th)

* Enrichment required for startup, not at “equilibrium”

Preliminary Grouping of Nuclear Power Alternatives: Two-Stage Recycle

Two-Stage Recycle Hierarchy:

- Limited or Continuous
- Critical or Sub-Critical
- Spectrum for Stage-1: Thermal; Intermediate; Fast
- Spectrum for Stage-2: Thermal; Intermediate; Fast
- Incoming Fuel Material: U; Th; U/Th
- Recycled Elements: U; Pu; MA; All TRU; Th; Fission Products
- Requires Enrichment?: No; Yes
- Recycle to 1-st Stage?: No; Yes

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Example: Two-Stage Recycle

Limited or Continuous	Reactivity by Stage	Spectrum 1st Stage 2nd Stage	Incoming Feed Fuel Material	Recycled Elements	Requires Enrichment?	Recycle to Stage 1?	Example Fuel Cycle Option
Limited	Critical Critical	Thermal Thermal	U	TRU	Yes	No	PWR(LEU) to HTGR(TRU/IMF)
Limited	Critical Critical	Thermal Thermal	U	Pu,RU	Yes	No	PWR(LEU) to PWR(MOX)
Limited	Critical Subcritical	Thermal Fast	U	TRU	Yes	No	PWR(LEU) to ADS(TRU)
Limited	Critical Critical	Thermal Thermal	U	RU/TRU and some FP	Yes	No	PWR(LEU) to HWR(DUPIC)
Continuous	Critical Critical	Thermal Fast	U	TRU,RU	Yes	No	PWR(LEU) to SFR(TRU/U*)

Closing Remarks

- **Overall, the resulting Fuel Cycle Options and Grouping will:**
  - be comprehensive for the entire range of potential fuel cycle characteristics that affect performance with respect to the high-level evaluation criteria
  - be grouped based on the performance to facilitate the fuel cycle evaluation and screening
  - be clearly explainable as to the content of the list and the corresponding groups
  - identify “representative option(s)” for each group to be explicitly evaluated for screening fuel cycles, with the preference for only a single representative option in each group
  - facilitate placement of any proposed new specific fuel cycle option into an existing group, allowing immediate assessment of the potential performance and identification of any benefits that would be associated with such options

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