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Features, Events and Processes for the Used Fuel Disposition Campaign

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FEATURES, EVENTS AND PROCESSES (FEPS) FOR THE USED FUEL DISPOSITION CAMPAIGN

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The Used Fuel Disposition (UFD) Campaign within DOE-NE is evaluating storage and disposal options for a range of waste forms and a range of geologic environments. To assess the potential performance of conceptual repository designs for the combinations of waste form and geologic environment, a master set of Features, Events, and Processes (FEPs) has been developed and evaluated. These FEPs are based on prior lists developed by the Yucca Mountain Project (YMP) and the international repository community.

The objective of the UFD FEPs activity is to identify and categorize FEPs that are important to disposal system performance for a variety of disposal alternatives (i.e., combinations of waste forms, disposal concepts, and geologic environments). FEP analysis provides guidance for the identification of (1) important considerations in disposal system design, and (2) gaps in the technical bases. The UFD FEPs also support the development of performance assessment (PA) models to evaluate the long-term performance of waste forms in the engineered and geologic environments of candidate disposal system alternatives.

For the UFD FEP development, five waste form groups and seven geologic settings are being considered. A total of 208 FEPs have been identified, categorized by the physical components of the waste disposal system as well as cross-cutting physical phenomena. The combination of 35 waste-form / geologic environments and 208 FEPs is large; however, some FEP evaluations can cut across multiple waste/environment combinations, and other FEPs can be categorized as not-applicable for some waste/environment combinations, making the task of FEP evaluation more tractable.

A FEP status tool has been developed to document progress. The tool emphasizes three major areas that can be statused numerically. FEP Applicability documents whether the FEP is pertinent to a waste/environment combination. FEP Completion Status documents the progress of the evaluation for the FEP/waste/environment combination. FEP Importance documents the potential importance for the FEP/waste/environment combination to repository performance.

I. INTRODUCTION

This paper describes the UFD team's progress[1] in identifying and categorizing features, events, and processes (FEPs) in support of the Used Fuel Disposition (UFD) Campaign of the U.S. Department of Energy, Office of Nuclear Energy (DOE NE), Fuel Cycle Technology (FCT) Program.

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II. IDENTIFICATION OF POTENTIAL DISPOSAL ALTERNATIVES

In collaboration with the Nuclear Energy Advanced Modeling and Simulations (NEAMS) Waste Integrated Performance and Safety Code (IPSC),[1] a set of six potential waste form type groupings (Table 1) and eight potential disposal concept/geologic setting groupings (Table 2) were identified to define the expected range (based on current knowledge) of disposal system concepts, engineered designs, and geologic settings and conditions.

TABLE 1. Groupings of Potential Waste Form Types

Group Number	Waste Form Type	Description
1	Used Nuclear Fuel (UNF)	e.g., Commercial, DOE-Owned, HTGR
2	High-Level Waste (HLW) Glass	Current (e.g., borosilicate) and future (e.g., no minor actinides)
3	HLW Glass Ceramic / Ceramic	Current (glass bonded sodalite) and future (e.g., from electrochemical processing)
4	HLW Metal Alloy	From electrochemical or aqueous reprocessing, cermets
5	Lower Than HLW (LTHLW)	Class A, B, and C, and GTCC
6	Other	Molten salt, electro-chemical refining waste, etc.

Note: HTGR = High-temperature gas-cooled reactor; GTCC = Greater than Class C.

The groupings in Table 1 and Table 2 result in 35 combinations (ignoring the placeholder *Other* groups) of waste form types and disposal concepts/geologic settings that broadly define the range of potential alternative disposal system designs that might need to be evaluated by the UFD Campaign. It should be noted that within any single alternative disposal system design there may be important sub-designs (e.g., waste emplacement geometry, thermal loading, engineered component design and materials) and/or conditions (e.g., saturated vs. unsaturated flow, boiling vs. non-boiling temperature, reducing vs. oxidizing chemistry) that may further delineate the range of technical capabilities required for evaluation.

III. POTENTIAL WASTE FORMS

In accordance with DOE-NE R&D Objective 3 (Develop Sustainable Nuclear Fuel Cycles), three nuclear fuel cycle options are now under consideration: Once-Through (i.e., Open Cycle); Modified Open Cycle; and Full Recycle (i.e., Closed Cycle).[2] These fuel cycle options will produce used nuclear fuel (UNF) and/or high-level waste (HLW) derived from reprocessing of UNF. Note that the terms *used nuclear fuel* and *spent nuclear fuel* (SNF) are used somewhat interchangeably in this paper. (UNF has been irradiated, but may have further use in advanced fuel cycles. SNF is intended for disposal. As the overall energy system evolves, fuels can shift from UNF to SNF or vice versa.) The potential waste forms to be considered by the FCT Program and the UFD Campaign include (1) the current inventory of UNF and HLW waste forms, and (2) waste forms that may be generated in the future from the currently-operating reactors and from reactors that may be built under any of the three fuel cycle options.

TABLE 2. Groupings of Potential Disposal Concepts and Geologic Settings

Group Number	Disposal Concept / Geologic Setting	Description
1	Surface Storage	Long-term interim storage at reactors or at centralized sites
2	Shallow Disposal	Depths <= 100 m (e.g., near-surface disposal, LTHLW sites)
3	Mined Geologic Disposal (Hard Rock, Unsaturated)	Granite/crystalline or tuff (Depths > 100 m)
4	Mined Geologic Disposal (Hard Rock, Saturated)	Granite/crystalline or tuff (Depths > 100 m)
5	Mined Geologic Disposal (Clay/Shale, Saturated)	Clay/shale (Depths > 100 m)
6	Mined Geologic Disposal (Salt, Saturated)	Bedded or domal salt (Depths > 100 m)
7	Deep Borehole Disposal	Granite/crystalline (Depths ~ 1000 m or deeper)
8	Other	Sub-seabed, carbonate formations, etc.

Table 1 organizes the range of potential current and future waste forms into a comprehensive, yet manageable set of categories of waste forms having similar characteristics. These waste form groupings may be updated as the list of fuel cycle options and/or waste form alternatives matures. Detailed descriptions of the potential waste forms are provided in Cunnane.[3]

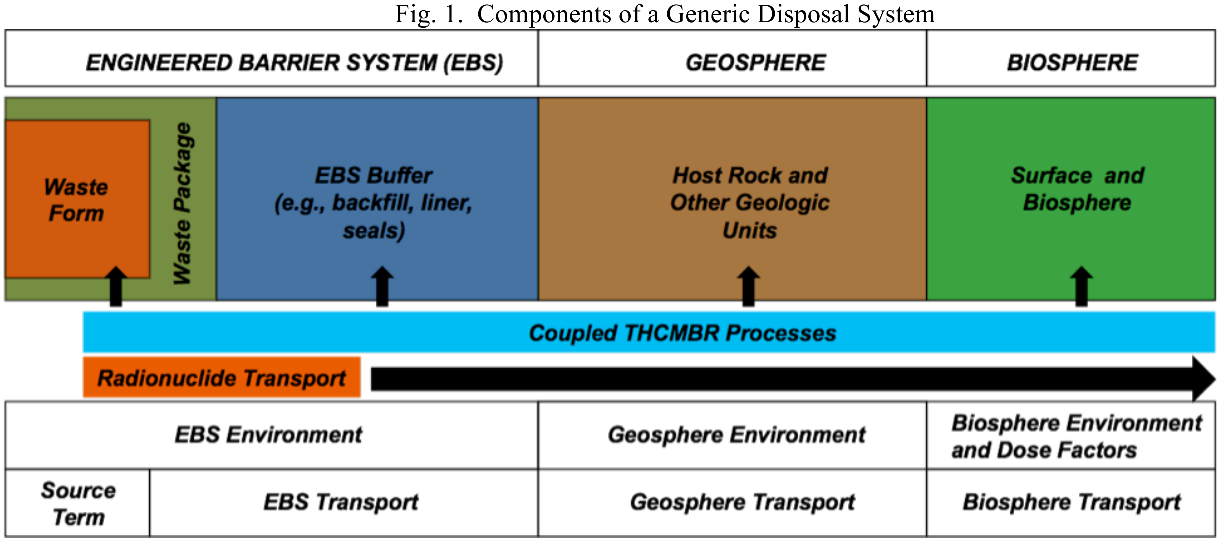
IV. IDENTIFICATION OF GENERIC DISPOSAL SYSTEM COMPONENTS

Both the UFD FEPs and the NEAMS Waste IPSC FEPs support the development of PA models to evaluate the long-term performance of waste forms in the engineered and geologic environments of a radioactive waste disposal system. This requires consideration of the coupled thermal, hydrologic, chemical, mechanical, biological, radiological (THCMBR) processes that govern radionuclide movement through the disposal system for a range of candidate waste forms, disposal concepts and designs, engineered and geologic environments, and associated conditions over a broad range of time and length scales. The potential range of UFD disposal system alternatives is represented by the 35 combinations of waste form types and disposal concepts/geologic settings.

To develop a conceptual understanding of the design components, physical domains, and phenomena that may be potentially relevant to the 35 disposal system alternatives, it is useful to identify the key common system components and phenomena. Figure 1 shows[1] a conceptualization of a generic disposal system that includes components, domains, and phenomena common to most of the 35 disposal system alternatives. The top half of Figure 1 shows the physical domains of the generic disposal system. The generic system contains three domains: the engineered barrier system (EBS), the geosphere, and the biosphere. Each of these three domains contains sub-domains: waste form, waste package, and buffer for the EBS; host rock and other geologic units for the geosphere; and the land surface for the biosphere. The bottom half of Figure 1 shows the phenomena that can affect each of these domains and sub-domains. These phenomena include, at a high level, the coupled THCMBR processes that describe (1) waste form degradation and the source term, (2) radionuclide transport through the EBS, (3) radionuclide transport through the host rock and surrounding geologic units (i.e., the geosphere), and (4) radionuclide transport, uptake, and health effects in the biosphere. In addition to their direct effects on radionuclide transport, the coupled THCMBR processes also influence the physical and chemical environments in the EBS, geosphere, and biosphere, which in turn affect water movement, degradation of EBS components, and radionuclide transport.

The terms near field (or near-field environment) and far-field (or far-field environment) are also commonly used to describe the physical domains of a disposal system. The near field encompasses the EBS as well as the interface with, and adjacent portion of, the host rock that experience durable (but not necessarily permanent) changes due to the presence of the repository (e.g., hydro-mechanical alteration due to tunnel excavation, thermal-chemical alteration due to waste emplacement). The far field encompasses the remainder of the geosphere and the biosphere.

Fig. 1. Components of a Generic Disposal System



V. FEP IDENTIFICATION AND CATEGORIZATION

Historical FEP identification by the Nuclear Energy Agency (NEA)[4,5] and in support of Yucca Mountain Project (YMP)[6] produced a comprehensive set of FEPs applicable to a range of disposal system alternatives. The development of a comprehensive set of UFD FEPs, in collaboration with the NEAMS Waste IPSC, is based on the NEA and YMP FEPs and is supported by a UFD FEP categorization scheme that is similar to the NEA categorization scheme.[4]

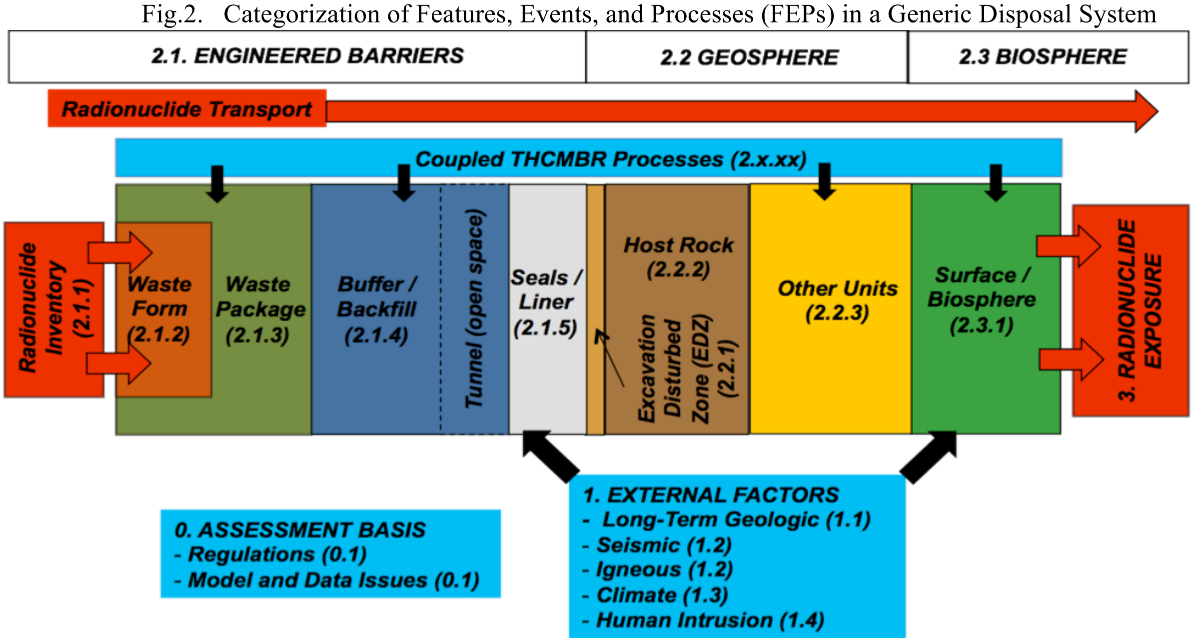
The UFD categorization scheme, illustrated[1] schematically in Figure 2, is based on a set of generic domains (features) that are present in most disposal system concepts. Note that the generic features in Figure 1 are subsystem components (i.e., additional details) of the three physical domains (EBS, Geosphere, Biosphere) in Figure 1. Figure 2 also illustrates how each of the generic features can be acted upon by events (i.e., External Factors) and/or THCMBR processes and indicates FEP categories that control the PA model calculations (i.e., Assessment Basis and Radionuclide Exposure).

An important attribute of the UFD categorization scheme is a hierarchical FEP numbering system that groups similar FEPs together. The numbers associated with various domains, features, events, and processes in Figure 3 correspond to the FEP numbering system. Across the disposal system domains, there is a consistent structure and numbering scheme for the features (2.x.01 contains the first feature, 2.x.02 contains the second feature, etc.) and the processes (2.x.07 contains mechanical processes, 2.x.08 contains hydrologic processes, etc.).

The development of a preliminary set of UFD FEPs potentially relevant to the range of disposal system alternatives and the generic disposal system components and phenomena considered the following information:

- Approximately 1,650 FEPs from 10 different national radioactive waste disposal programs contained in the NEA FEP list.[4,5] The NEA FEPs cover a wide range of disposal system designs and geologic settings.
- 374 FEPs from the YMP FEP list.[6] The YMP FEPs are specific to the YMP design concept in an unsaturated, fractured tuff. The NEA FEPs were considered in the development of the YMP FEP list.
- A preliminary list of 92 Phenomena Identification and Ranking Table items (PIRTs) developed for the NEAMS Waste IPSC.[7] The Waste IPSC PIRTs were developed from the NEA FEPs and the YMP FEPs, but were limited to a generic EBS domain.

Fig.2. Categorization of Features, Events, and Processes (FEPs) in a Generic Disposal System



Because the NEA FEPs are a compilation of FEPs from ten different disposal programs they contain: (1) considerable redundancy (e.g., the same FEP is often identified ten different times - once by each program); (2) varying levels of detail (e.g., the scope captured by a single broad FEP in one program may captured in several finer FEPs in another program); (3) overlapping scope (due to the coupled nature of the THCMBR processes, many of the FEPs are related and therefore not mutually exclusive); and (4) some site-specific phenomena. To make the NEA FEPs more broadly applicable to a range of disposal alternatives, the NEA FEPs were grouped and classified so that FEPs of similar or related scope could be consolidated, generalized, and given a more consistent level of detail. The resulting list of few hundred *working* FEPs captured the range of phenomena encompassed by the full set of the approximately 1,650 NEA FEPs. The approach used to consolidate the NEA FEPs to a more organized and focused working FEP list for YMP is described in Freeze et al[8] and BSC.[9] The approach includes many generally applicable steps and was followed in the development of the general EBS PIRTs[7] and in the development of the UFD FEPs.

UFD FEP identification involved expanding the EBS PIRT list beyond the EBS domain to include the geosphere and biosphere domains (i.e., the entire disposal system). This expansion was accomplished by (1) reviewing the existing EBS PIRTs, (2) examining the list of geosphere and biosphere YMP FEPs (which implicitly capture the NEA FEPs) and generalizing them for potential relevance to the UFD disposal alternatives, (3) reviewing FCT planning documents, (4) brainstorming by UFD and NEAMS Waste IPSC subject matter experts, and (5) cross-mapping of the FEPs with the categorization scheme.

The resulting set of 208 preliminary UFD FEPs is listed in Freeze, et al.[1] Each UFD FEP is defined by a *Description* at a broad level of detail such that it is potentially applicable to the full range of disposal system alternatives. For example, *Sorption of Dissolved Radionuclides in the EBS* is potentially relevant to all waste form types and disposal concepts/geologic settings. Each FEP is further defined by additional details under *Associated Processes*. The level of detail collectively captured by the FEP Descriptions and Associated Processes is appropriate for the current FEP identification step of FEP analysis. The technical scope of the 208 preliminary UFD FEPs captures the full range of potentially relevant phenomena (and associated time- and length-scales) represented by the NEA and YMP FEP lists for the range of disposal system alternatives encompassed by the 35 combinations of concepts/settings and waste form types. For traceability, *Related YMP FEPs* are mapped to each UFD FEP. The YMP FEPs are in turn mapped to the NEA FEPs.[10] The smaller number of UFD FEPs relative to YMP is due to consolidation and generalization of some FEPs (i.e., a broader level of detail) to better represent a broader scope more applicable to a range of disposal system alternatives, rather than to a specific design and geologic setting.

VI. THE FEP STATUS TOOL

The combination of 208 FEPs with the 35 waste forms / geologic setting categories leads to a truly large parameter space for evaluation. Fortunately, many evaluations can handle multiple waste form and/or geologic setting situations for a given FEP, or multiple FEPs for a given waste form and/or geologic setting situation. The FEP status tool was developed to track progress in these evaluations. The heart of the tool is a status block for each of the 208 x 35 combinations (Fig. 3). This status block is used repeatedly in a large Excel file (about 5 MB). The file is organized into one sheet per FEP. Each sheet is organized with column pairs for the waste form categories, and sets of seven rows for each geologic setting. Thus, each sheet has 35 status blocks for the defined categories. (Actually, there are 48 status blocks because there are the *other* categories for both the waste form and geologic setting.)

Fig. 3. Status block for each combination of FEP number, waste form, and geologic environment.

Block of Items for each Waste Form/Environment combination	
Applicability (#)	Applicability of FEP for *WF* & *Environment* (words)
Completion Status (#)	Completion Status (words)
Importance (#)	Importance (words)
FEP Argument Summary	
Remarks	
Reference(s), could be a hyperlink	
Responsible Org / Individual	Number of Responsible Organizations

The applicability, completion status, and importance numbers at the upper left of the status block are quantitative metrics of progress. They vary between 0.0 and 1.0, with 1.0 being applicable, complete, and of key importance for this FEP and combination of waste form and geologic setting.

The status block also includes space to discuss these three metrics (word wrap allows longer discussions than the block size implies). Below the three metrics is space to briefly summarize the FEP inclusion or exclusion argument, record any pertinent remarks, and point to the reference(s) in which the more detailed evaluation is documented. Finally, the block includes two cells at the bottom to identify the responsible organization and individual, and to indicate the number of organizations that have proposed to take responsibility for the evaluation. The latter block is used to determine which of the 208 x 35 combinations are over- or under-subscribed in the work scope that has been built from the bottom-up.

The status tool includes two *statistics* sheets. Each is organized with triplets of columns (for the three metrics) for each of the 48 combinations of waste form and geologic setting. There are rows for each of the 208 FEPs, as well as rows for summary categories. In the *statistics* sheet, x.x.x.0 averages x.x.x.n, for all n, x.x.0.0 averages x.x.n.0 values, x.0.0.0 averages x.n.0.0 values, and *the average of top level categories* averages n.0.0.0 values. There is also a direct average of all the individual FEPs (assumes equal weighting, rather than weighting based on the number of sub-items to any summary category). The *binary statistics* sheet is identical to the *statistics sheet*, except that the individual metrics (for the 208 x 48 situations) are rounded to either 0.0 or 1.1. The summary categories in the *binary statistics* sheet are the unrounded averages of the rounded metrics. Color codes (red, yellow, green) in various shades of brightness make the metrics and the average metrics visually understandable.

The status tool also includes an extensive legend (read-me) sheet, a revision history tracking sheet, a sheet to track responsible organizations and individuals, a sheet to track identified technical gaps, and sheets to document the waste form and geologic setting categories in detail.

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