A New Approach for Feature, Event, and Process (FEP) Analysis of UNF/HLW Disposal – 14314

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ABSTRACT

This paper describes a new organizational structure for the FEPs that characterize the potential post-closure performance of a deep geologic disposal system (i.e., repository) for used nuclear fuel (UNF) and high-level radioactive waste (HLW). FEPs are traditionally organized using a classification scheme that is based on two overlapping sets of categories: features (e.g., waste form, waste package, backfill, host rock, etc.) and multi-physics processes (e.g., thermal, chemical, mechanical, hydrologic). The categories are overlapping in the sense that a specific FEP (e.g., flow through the waste package) may be classified both by a feature category (e.g., waste package) and by a process category (e.g., hydrologic). As a result, related FEPs are not always mapped to the same category and it can be difficult to group and/or find all related FEPs within a FEP list. The new FEP organizational structure is represented using a FEP classification matrix and is based on the concept that a FEP is typically a process or event acting upon or within a feature. The FEP matrix provides a two-dimensional organizational structure that consists of a Features axis that defines the “rows” and a Processes/Events axis that defines the “columns”. The two-dimensional structure of the FEP matrix is an improvement over the traditional classification scheme because it better facilitates: (1) the mapping of each specific FEP (i.e., a process or event acting upon a feature) to a single location in the FEP matrix, namely the matrix cell at the intersection of the relevant feature row and process/event column; (2) the grouping of related FEPs in a single matrix cell, row, or column; and (3) a more intuitive FEP numbering and documentation system. As a result, the FEP matrix approach makes it easier to identify groups of related FEPs and thereby better inform post-closure performance assessment (PA) models. The FEP matrix approach is currently being applied to develop a comprehensive set of FEPs for a generic salt repository, as part of a joint collaboration between the U.S. and German repository research programs. The goal of the collaboration is to populate an international FEP database for salt repositories.

INTRODUCTION

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE), Office of Used Nuclear Fuel Disposition (UFD) is conducting research to enable disposal of UNF and HLW in a variety of geologic media and generic repository concepts. To assess the potential performance of various repository options, a FEP analysis of phenomena relevant to the post-closure period of deep geologic disposal systems was performed [1, 2]. Formal FEP analysis includes:

- FEP identification – the development and classification of a comprehensive list of FEPs that cover the entire range of phenomena that are potentially relevant to the long-term performance of a repository system, and;

- FEP screening – the specification of a subset of important FEPs that individually, or in combination with other FEPs, contribute to long-term performance.

FEP analysis informs the construction of post-closure PA models of UNF/HLW repositories and the associated uncertainty and sensitivity analyses. The important (screened in) FEPs must be included in the post-closure PA model. The exclusion of a FEP from the PA model (e.g., by low probability, by low consequence, or by inconsistency with regulation) must be supported by a defensible rationale. The included FEPs are indicative of technical areas where research and development (R&D) focus may be necessary. R&D may also be necessary to provide robust, defensible screening rationales for excluded FEPs. In addition, the FEP analyses, PA model results, and R&D focus areas all inform the safety case – the overarching, integrated collection of qualitative and quantitative arguments, evidence, and analyses that substantiate the safety, and the level of confidence in the safety, of a geologic repository [3, 4].

During FEP analysis, PA model construction, and safety case development it is often necessary to evaluate the importance and/or the level of knowledge and understanding of certain topical areas (i.e., the potential behavior of a specific repository feature or the potential effects of a specific long-term process). The ability to examine the complete set of FEPs related to the topical area of interest greatly facilitates these types of evaluations. This paper describes a new FEP organizational structure, the FEP classification matrix, designed specifically to easily group related FEPs within a FEP list. The FEP matrix approach is an improvement over traditional FEP classification schemes, thereby better supporting FEP analyses, PA model construction, and safety case development.

DISCUSSION OF FEP CLASSIFICATION METHODS

The new FEP classification matrix approach is described in the following subsections. The description includes: (1) a review of traditional FEP identification and classification methods, using a generic FEP list developed by the UFD as an example; (2) a summary of the FEP matrix approach, demonstrated by an application to a set of generic salt repository FEPs; and (3) a new FEP numbering scheme and documentation template, compatible with the FEP matrix, but also traceable to traditional FEP numbering schemes.

Traditional FEP Classification Scheme

The UFD has identified FEPs for post-closure phenomena relevant to four different generic deep geologic disposal concepts: mined crystalline/granite, mined shale/clay, mined salt, and deep borehole crystalline [2]. The UFD list of 208 FEPs derives from prior FEP analyses, such as those summarized in the Nuclear Energy Agency (NEA) International FEP Database [5, 6] and other earlier FEP lists [7]. The UFD FEPs are organized using a hierarchical numbering and categorization scheme adopted from the NEA International FEP Database [5]. This is consistent with FEP analyses performed by most UNF/HLW repository programs worldwide, most of whom have also traditionally adopted the NEA classification scheme. The NEA numbering and categorization hierarchy is shown schematically in Fig. 1.

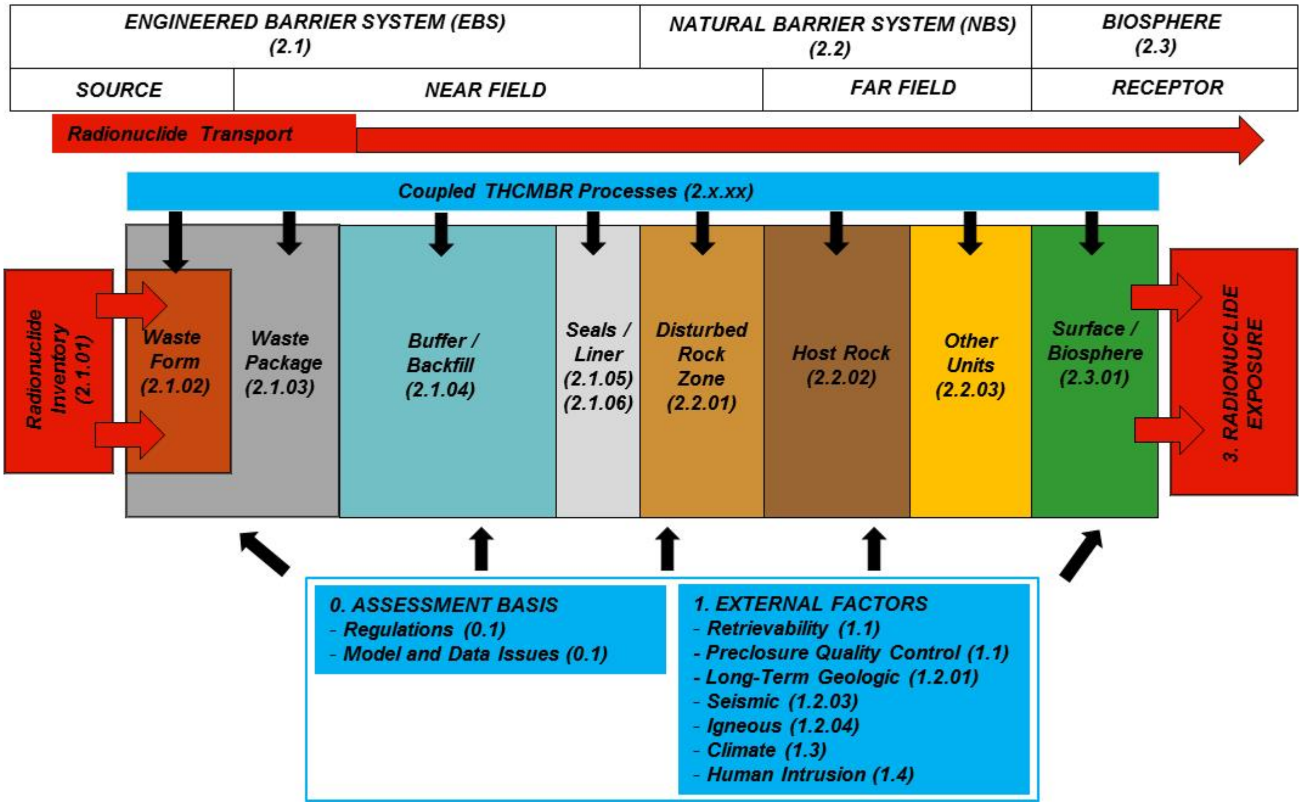

Fig. 1. Traditional NEA Hierarchical FEP Numbering and Categorization Scheme.

The hierarchical classification levels are organized around the common regions and features of a disposal system: the Engineered Barrier System (EBS) which includes the wastes (e.g., inventory and waste forms) and engineered features (e.g., waste container/package, buffer/backfill, and seals); the Natural Barrier System (NBS) or geosphere which includes the disturbed rock zone (DRZ), host rock, and other geological units; and the Biosphere which includes the surface environment and receptor characteristics. In addition to the region/feature-based categories, there are also categories for the Assessment Basis and External Factors.

The classification hierarchy is established using the FEP numbering scheme. The first four digits of a FEP number correspond to hierarchical classification levels:

- 4 Layers (first-level entries having the form X.0.00.00). These Layers (X) are:
  - 0 = Assessment Basis,
  - 1 = External Factors,
  - 2 = Disposal System Factors, and
  - 3 = Radionuclide/Contaminant Factors.

- 12 Categories (second-level entries having the form X.Y.00.00). Examples of Categories under Disposal System Factors (2.Y.00.00) are:
  - 2.1 = Wastes and Engineered Features (i.e., the EBS),
  - 2.2 = Geologic Environment (i.e., the NBS), and
  - 2.3 = Surface Environment (i.e., the Biosphere).

- 43 Headings (third-level entries having the form X.Y.ZZ.00). Examples of Headings under Disposal System Factors – Wastes and Engineered Features (2.1.ZZ.00) are:
  - 2.1.01 = Inventory,
  - 2.1.02 = Waste Form,
  - 2.1.03 = Waste Container,
  - 2.1.04 = Buffer/Backfill,
  - 2.1.05 = Seals,
  - 2.1.06 = Other EBS Materials,
  - 2.1.07 = Mechanical Processes,
  - 2.1.08 = Hydrologic Processes,
  - 2.1.09 = Chemical Processes – Chemistry and Transport,
  - 2.1.10 = Biological Processes,
  - 2.1.11 = Thermal Processes,
  - 2.1.12 = Gas Sources and Effects,
  - 2.1.13 = Radiation Effects,
  - 2.1.14 = Nuclear Criticality.

This classification hierarchy provides an organizational structure for the 208 UFD generic FEPs, which all have UFD FEP Numbers in the form X.Y.ZZ.nn. The first four digits of a FEP number serve to group related FEPs by their Layer, Category, and Heading. However, at the lowest classification level (Heading), there can be some overlap. For example, the Heading entries shown above for Disposal System Factors – Wastes and Engineered Features consist of a mixture of feature-based Headings (e.g., 2.1.01 through 2.1.06) and thermal-hydrologic-mechanical-chemical-biological-radiological (THCMBR) process-based Headings (e.g., 2.1.07 through 2.1.14). Because an individual FEP is typically a process (or event) acting upon a feature (or several features), many FEPs can be mapped to more than one Heading in this traditional NEA-based classification scheme (e.g., an individual FEP can often be mapped to both a feature-based Heading and to a process-based Heading). For example, a specific FEP (e.g., flow through the waste package) could be mapped to either its feature category (e.g., 2.1.03 Waste Container) or its process category (e.g., 2.1.08 Hydrologic Processes). As a result, this organizational structure makes it difficult to find a unique “home” for all FEPs; related FEPs may not always be mapped under the same Heading making it difficult to completely group and/or find all related FEPs within a FEP list.

FEP Classification Matrix Approach

In the traditional NEA-based numbering and categorization scheme described above, the overlap of feature-based and process-based categories (i.e., Headings) at the same hierarchical classification level makes it difficult to completely map and group all related FEPs together. To overcome this shortcoming, a new FEP organizational structure was developed – the FEP classification matrix. The FEP matrix approach is refined from an earlier application formulated by Sandia National Laboratories [7], and is based on the concept that a FEP is typically a process or event acting upon or within a feature. Thus, the FEP matrix provides a two-dimensional organizational structure that consists of a Features axis that defines the “rows” and a Processes/Events axis that defines the “columns”. The two-dimensional structure makes it easier to: (1) map a specific FEP (i.e., a process or event acting upon a feature) to a single location in the FEP matrix, namely the matrix cell at the intersection of the relevant feature row and process/event column; and (2) group related FEPs in a single matrix cell, row, or column. An example FEP matrix is shown in Fig. 2.

The example FEP matrix shown in Fig. 2 is being developed as part of a joint collaboration between the U.S. and German repository research programs to investigate generic UNF/HLW salt repository concepts. The Features column contains a few salt-repository specific components, but otherwise the example FEP matrix for a salt repository contains generic Features and Processes and Events that could apply to most repository concepts.

The Features axis is organized to generally correspond to the direction of potential radionuclide migration, from the waste to the biosphere (i.e., from left to right in Fig. 1). Features are organized in hierarchical categories. At the top level (Regions) are: Waste and Engineered Barriers (e.g., the EBS), Geosphere (e.g., the NBS), Surface (e.g., the Biosphere), and System. The Surface Region is designed to capture FEPs that are relevant to the calculation of dose to the receptor, which may include radionuclide movement above the subsurface. The System Region is designed to include FEPs that are potentially relevant to the repository system as a whole. As shown in Fig. 2, there are lower-level categories (e.g., individual Features) below each of the top-level Regions. For example, in the Waste and Engineered Barriers Region, individual Features are: Waste Form and Cladding, Waste Package and Internals, Buffer/Backfill, Emplacement Tunnels and Mine Workings (i.e., the open air spaces that may be present in non-backfilled open-mode designs), and Seals/Plugs. Below each of these Feature categories, a further level of detail may also be specified (e.g., under Waste Form there can be a distinction between UNF and HLW and commercial and defense waste). It should be noted that the hierarchical Feature axis categories are fairly generic at the Region level, but may become disposal option specific at the lower levels. For example, the Feature sub-categories below the Host Rock and below the Other Geologic Units in Fig. 2 are specific to a salt repository.

Characteristics, Processes, and Events / Features	Characteristics	Processes											Events					
		Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (long timescale)	Other	Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (short timescale)	Other
Waste and Engineered Barriers Region																		
Waste Form and Cladding																		
• Commercial SNF & Cladding																		
• Commercial HLW Glass																		
• Naval SNF & Cladding																		
• Defense SNF & Cladding																		
• Defense HLW																		
• Other																		
Waste Package and Internals																		
• Commercial SNF																		
• Commercial HLW																		
• Naval																		
• Defense SNF																		
• Defense HLW																		
• Other Packages																		
Buffer/Backfill																		
• Waste Package Buffer																		
• Tunnel/Drift/Room Backfill																		
Emplacement Tunnels/Drifts and Mine Workings																		
• Open Excavations																		
• Drift Support																		
• Liners																		
• Other																		
Seals/Plugs																		
• Drift/Panel Seals/Closures																		
• Shaft Seals																		
• Plugged Boreholes																		
Geosphere / Natural Barrier Region																		
Host Rock (Repository Horizon)																		
• Bedded or Domal Salt																		
• Disturbed Rock Zone																		
• Interbeds / Seams																		
Other Geologic Units																		
• Aquifer(s)																		
• Unsaturated Zone																		
• Pressurized Brine Reservoir(s)																		
Surface Region																		
Biosphere																		
• Natural Surface and Near-Surface Environment																		
• Flora and Fauna																		
• Humans																		
• Food & Drinking Water																		
• Dwellings and Man-Made Surface Features/Materials																		
System Region																		
Repository System																		
• Assessment Basis																		
• Preclosure/Operational																		
• Other Global																		

Fig. 2. FEP Matrix.

The Processes and Events axis contains categories for FEPs that can act upon a Feature. A description of each of the Processes and Events categories is provided below. Two categories require some clarification:

- **Characteristics** are used to describe the properties of the features that need to be evaluated. The characteristics are not typically FEPs in the sense that they cannot be screened in or out, but the characteristic information (and changes to that information) influences the screening of the other FEPs. For example, the initial radionuclide inventory is considered a characteristic of the waste form and material properties are considered characteristics of the geosphere features.

- **Thermal** processes (conduction, radiation, convection) are generally treated in a coupled fashion with the process affected by thermal conditions. For example, the processes are referred to as thermal-mechanical, thermal-hydrologic, or thermal-chemical to indicate the principal couplings considered. The convention used to describe coupled processes places the causative process first and the affected process second. For example, thermal-chemical processes are those in which the thermal environment affects the behavior of the chemical environment. Generally, the reverse coupling (in this example, the effect of chemistry change on the thermal environment) is significantly weaker than the forward coupling. There is also an independent thermal process category, but past experience suggests it is usually difficult to isolate the thermal-only aspects of most FEPs.

A brief description of the Processes follows:

- **Mechanical** processes include phenomena that affect drift degradation, that affect the degradation of engineered features, and that change rock properties such as porosity. These mechanical processes include salt creep, rockfall, drift collapse, stress corrosion cracking, hydrogen embrittlement, buckling, floor heave, and weathering, among others. **Thermal-mechanical** processes include thermal stresses and their corresponding effects on rock mass strength and degradation.

- **Hydrologic** flow processes include precipitation, infiltration, runoff, unsaturated zone flow, flow diversion, capillarity, matrix imbibition, evaporation, condensation, and saturated zone flow. **Thermal-hydrologic** processes include evaporation, condensation, vapor flow, and temperature-dependent property changes.

- **Chemical** processes include phenomena that affect the chemical environment and degradation mechanisms of engineered features and the chemical environment in the natural system. These chemical processes include such phenomena as dissolution, precipitation, reduction and oxidation, salt deliquescence, general corrosion, localized (or crevice) corrosion, alteration, and solubility. **Thermal-chemical** processes include evaporation, mineral precipitation, dissolution, and effects on thermal-chemical properties.

- **Biological** (and microbiological) processes include the potential effects of microorganisms on other processes relevant to performance, such as microbial effects on chemical processes. **Thermal-biological** processes include temperature-dependent effects.

- **Transport** includes such processes as advection, diffusion, dispersion, matrix diffusion, retardation, and colloid stability and filtration. These processes may occur within the EBS, NBS, and/or Biosphere. **Thermal-transport** processes include temperature-dependent effects. Transport processes are typically strongly dependent on the other THCMBR processes and couplings.

- **Thermal** processes include only those broad-based temperature dependencies that are not coupled to other THCMBR processes.

- **Radiological** processes include the potential effects of ionizing radiation from the decay of radioactive materials on other processes potentially relevant to performance, such as chemistry. Specific radiological processes include radiolysis. Radiological processes also include radiological exposure to the receptor and the resulting doses.

- **Long-Term Geologic** processes include tectonic activity, metamorphism, diapirism, subsidence, and dissolution.

- **Climatic** processes include natural effects that may produce changes in the regional and local climate.

- **Human Activities (Long Timescale)** includes human-initiated effects on the climate and the surface and subsurface environment.

- **Other** is reserved for processes that do not fit into any of the other categories. Examples include processes related to the calculation of the dose to the receptor such as ingestion, inhalation, and exposure.

A brief description of the Events follows:

- **Nuclear Criticality** events include initiators of sequences of events or processes that could lead to configurations that have potential for criticality in the EBS or NBS. For a criticality event to occur, the appropriate combination of materials (neutron moderators, neutron absorbers, fissile materials, or isotopes) and geometric configurations favorable to criticality must exist. During design, criticality analyses are performed to demonstrate that the initial emplaced configuration of the waste form remains subcritical, even under flooded conditions. For a configuration to have potential for criticality, all of the following conditions must occur: (1) sufficient mechanical or corrosive damage to the waste package outer corrosion barrier to cause a breach, (2) presence of a moderator, i.e., water, (3) separation of fissionable material from the neutron absorber material or an absorber material selection error during the canister fabrication process, and (4) the accumulation or presence of a critical mass of fissionable material.

- **Early Failure** events include phenomena that lead to the failure of a feature or component at a time significantly faster than the design basis. An example is the through-wall penetration of a waste package due to manufacturing- or handling-induced defects, at a time earlier than would be predicted by mechanistic degradation models for a defect-free waste package. Another example is the early failure of a shaft seal.

- **Seismic** events include seismic activity that produces vibratory ground motion or fault displacement which affects the waste packages, the EBS, and/or the natural system pathways.

- **Igneous** events include igneous intrusion intersecting the repository, volcanic eruption from a volcanic vent that intersects the repository, and/or volcanic disturbance to the natural system pathways. Igneous intrusion considers the possibility that magma, in the form of a dike, could intrude into the EBS, destroying waste packages, and exposing the waste forms for potential mobilization of radionuclides. Volcanic eruption considers that a volcanic conduit (or conduits) intersects the repository, destroys waste packages, and erupts at the land surface. The volcanic eruption disperses volcanic tephra and entrained waste under atmospheric conditions, and deposits the contaminated tephra on land surfaces where the contaminated tephra becomes subject to redistribution by soil and near surface transport processes.

- **Human Activities (Short Timescale)** includes human intrusion events. Human intrusion is commonly addressed by a stylized calculation (typically specified by regulation) that simulates a future drilling operation in which an intruder drills a borehole that directly intersects a waste package causing a release of radionuclides that are subsequently transported into the natural system or up the borehole to the surface.

- **Other** is reserved for events that do not fit into any of the other categories. Examples include events such as meteor impacts, explosions, or crashes.

To demonstrate the applicability of the FEP matrix approach, a set of 208 generic salt repository FEPs were created [8], based on the 208 UFD FEPs for UNF and HLW and further informed by FEPs from salt repositories at WIPP (bedded salt) [9] and Gorleben (domal salt) [10]. These salt-repository-specific FEPs were mapped to the salt repository FEP matrix shown in Fig. 2; some FEPs mapped to a single matrix cell, some FEPs mapped to more than one matrix cell. To provide mapping to some of the Features and Feature sub-categories, some of the original 208 salt FEPs needed to be sub-divided. This typically occurred when an original FEP was broad-based and applied to multiple features. For example, FEPs for flow and transport typically applied to most if not all of the components of the engineered barriers and geosphere, and were therefore sub-divided into multiple FEPs – one for each Feature. The updated list of subdivided FEPs is provided in Ref. [3].

FEP-Matrix-Based Numbering Scheme and Documentation Template

To track the mapping of the individual FEPs to the FEP matrix cells, a new FEP-matrix-based numbering scheme was developed. The new FEP numbers are eight character alpha-numerics with the form FF.ff.PE.nn. The first group of characters (FF) indicates the Feature, as follows:

WF = Waste Form
WP = Waste Package
BB = Buffer/Backfill
MW = Emplacement Tunnels and Mine Workings
SP = Seals/Plugs
HR = Host Rock
OU = Other Geologic Units
BP = Biosphere
RS = Repository System

The second group of characters (ff) indicates the Feature sub-category, if applicable. As an example, under Seals/Plugs (SP) the following numbering would apply:

SP.00 = FEPs related to all the seals and plugs collectively (i.e., no sub-category)
SP.01 = FEPs related only to the drift/panel seals and plugs
SP.02 = FEPs related only to the shaft seals
SP.03 = FEPs related only to the borehole plugs

The third group of characters (PE) indicates the Process/Event category, as follows:

CP = Characteristics
TM = Mechanical and Thermal-Mechanical Processes
TH = Hydrological and Thermal-Hydrological Processes
TC = Chemical and Thermal-Chemical Processes
TB = Biological and Thermal-Biological Processes
TT = Transport and Thermal-Transport Processes
TR = Thermal
RA = Radiological
LG = Long-Term Geologic
CL = Climatic
HP = Human Activities (Processes)
OP = Other (Processes)
NC = Nuclear Criticality
EF = Early Failure
SM = Seismic
IG = Igneous
HE = Human Activities (Events)
OE = Other (Events)

The final group of characters (nn) is simply a sequential tracking number for FEPs in a specific cell, e.g., .01, .02, etc. As an example, a FEP describing hydrologic processes in the Disturbed Rock Zone would have a FEP number such as HR.02.TH.01. These new FEP numbers better indicate where a FEP is mapped in the FEP matrix classification scheme; and the Feature (FF) and Process/Event (PE) characters within the FEP numbers are more descriptive than strictly numeric identifiers. However, each individual FEP can also retain a traditional NEA-based FEP number if it is desired to maintain traceability to a prior FEP list.

In addition to developing the FEP matrix and associated FEP mappings, the joint U.S.-German collaboration has also developed a general template for the documentation associated with each individual FEP. The FEP template provides a structure to document the scope and screening of each individual FEP. It includes the following sections:

1. FEP Name and Definition
2. FEP Description
    - 2.1 General
    - 2.2 Concept Specific (e.g., bedded salt vs. domal salt)
    - 2.3 Properties and Parameter Values
    - 2.4 Related FEPs
3. Screening Decision
4. Screening Justification
5. Open Issues
6. References

The ultimate goal of the U.S.-German collaboration is to populate an international FEP-matrix-based relational database for salt repositories that can promote easy searching for FEPs and pertinent information. The populated FEP matrix will then be a useful tool for developing and documenting a robust safety case for a repository in salt rock.

CONCLUSIONS

A new organizational structure was developed for post-closure UNF/HLW repository FEPs – the FEP classification matrix. The FEP matrix provides a two-dimensional structure that consists of a Features axis that defines the matrix “rows” and a Processes/Events axis that defines the matrix “columns”. The two-dimensional classification structure of the FEP matrix is an improvement over the traditional NEA-based FEP classification scheme because it better facilitates: (1) the mapping of each specific FEP (i.e., a process or event acting upon a feature) to a single location in the FEP matrix, namely the matrix cell at the intersection of the relevant feature row and process/event column; (2) the grouping of related FEPs in a single matrix cell, row, or column; and (3) a more intuitive FEP numbering and documentation system. As a result, the FEP matrix approach makes it easier to identify groups of related FEPs and thereby better inform post-closure PA model construction and safety case development.

The FEP matrix approach is currently being applied to develop a comprehensive set of FEPs for a generic salt repository, as part of a joint collaboration between the U.S. and German repository research programs. The goal of the collaboration is to populate an international FEP database for salt repositories that can promote easy searching for FEPs and associated issues.

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