# *Influence of Nuclear Fuel Cycles on Uncertainty of Long-Term Performance of Geologic Disposal Systems*

## **Fuel Cycle Research & Development**

*Prepared for*
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*Used Fuel Disposition Campaign*

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# EXECUTIVE SUMMARY

Development and implementation of future advanced fuel cycles by the US Department of Energy (DOE) Fuel Cycle Technology Program (FCT), including those that recycle fuel materials, use advanced fuels different from current fuels, or partition and transmute actinide radionuclides, will impact the waste management system under study by the FCT Used Fuel Disposition (UFD) Campaign. The impact of advanced fuel cycles on disposal in mined geologic repositories is of interest in the international community,, and several countries, in addition to the US, have performed studies over the past decades [1-5]. These studies have evaluated the influence on (1) volume, mass, and space requirements for waste packages and repositories from changes in decay heat and waste form; (2) proliferation resistance; and (3) safety performance of the repository after closure.

In addition, some of these studies have also suggested that the removal of actinides and perhaps other radionuclides could beneficially reduce the uncertainties related to geologic disposal [2; 5]. This report examines this claim as related to US regulations for a theoretical, fully-closed advanced fuel cycle that removes actinides from the waste. In addition, this report examines the treatment of uncertainty, in general, within a performance assessment. Based on the discussion summarized below, the UFD Campaign can reasonably conclude that advanced fuel cycles, in combination with partitioning and transmutation, which remove actinides, will not materially alter the performance, the spread in dose results around the mean, the modeling effort to include significant features, events, and processes (FEPs) in the performance assessment, or the characterization of uncertainty associated with a geologic disposal system in the regulatory environment of the US.

## Uncertainty

Inclusion of uncertainty is an important aspect of evaluating the performance of a geologic disposal system. It is part of the regulatory definition of a performance assessment; for example, the Environmental Protection Agency (EPA) standards for the proposed Yucca Mountain repository, 40 CFR 197 [6, §197.12] state

> Performance assessment means an analysis that: …(3) Estimates the annual committed effective dose equivalent incurred by the reasonably maximally exposed individual, *including the associated uncertainties*, as a result of releases caused by all significant features, events, processes, and sequences of events and processes, weighted by their probability of occurrence (emphasis added).

### Three Sources of Uncertainty

If all the associated uncertainties related to geologic disposal could be quantified, they would be represented by the spread in the results about the calculated mean of the annual committed effective dose equivalent, the health measure used in current US regulations. In general, uncertainty about the dose derives from the unavoidable gaps in understanding about current and future behavior of the disposal system. The interpretation of the known data to develop a mathematical model and corresponding model parameters for analysis of performance can introduce further uncertainty. The uncertainty in the performance assessment of a geologic disposal system has typically been grouped with the three major aspects of the performance assessment: scenarios, models, and parameters. *Scenario uncertainty* is uncertainty as to (a) whether some unknown behavior or concept has been unknowingly omitted (i.e., whether the FEP and scenarios formed from these FEPs are comprehensive and complete), and (b) the most appropriate way to group the FEPs for modeling (logic). *Conceptual model uncertainty* is uncertainty about (a) the hypotheses and the appropriate conceptual model forms, and (b) the translation of the conceptual model into a mathematical model. *Parameter uncertainty* is uncertainty in the most appropriate parameter values to use in the mathematical model of the disposal system.

## Regulatory Focus for Uncertainty

The Nuclear Regulatory Commission (NRC) regulation, 10 CFR 63, which implements the EPA health standard for the proposed Yucca Mountain repository, specifically requires inclusion of parameter uncertainty, consideration of model uncertainty, and the technical basis for inclusion or exclusion of FEPs as part of scenario uncertainty [7]. But because some aspects of the uncertainty cannot be quantified or are not of regulatory interest, EPA and NRC also established additional requirements and guidance for treating uncertainty within the performance assessment. [1]

EPA and NRC have established general criteria on FEPs that are of regulatory interest; specifically, (1) only FEPs with probability greater than $10^{-8}$ annually; and (2) only FEPs that influence the time and magnitude of the dose. Although the regulatory period of the EPA health standard extends through the period of geologic stability (~$10^6$ yr for the proposed Yucca Mountain repository), only those FEPs found important in the first $10^4$ yr are to be considered beyond $10^4$ yr. Also, EPA and NRC require that general corrosion of the waste package be considered even if the FEP was not important in the first $10^4$ yr [6]. In addition, EPA and NRC adopted a strategy of describing the focus of interest for three common natural disruptive events: seismic events, igneous events, and climate change.

EPA and NRC also narrowed the focus of interest for speculative anthropogenic disruption to that of inadvertent human intrusion through a single exploratory borehole into the repository in their Yucca Mountain regulations [6]. The event is to occur when sufficient degradation of the package has occurred such that driller would not easily recognize the existence of the repository. Although the event could occur far in the future, the current state of human knowledge and technology is to be assumed. Dose to a driller is not thought pertinent since it only depends upon the characteristics of the waste, not the geologic disposal system. Rather, only dose to individuals in the accessible environment, at least 5 km away, is to be evaluated. In the stylized calculation, the borehole creates a fast path from the repository to an aquifer, but retains the remainder of the natural barrier in the aquifer, where transport of radionuclides might be reduced.

NRC also requires the use of multiple barriers in the geologic disposal system to compensate for residual uncertainty [7, p. 55747], specifically,

> Part 63 not only requires DOE to account for uncertainty in its performance assessment but also contains a number of other requirements (e.g., use of multiple barriers, performance confirmation program) to compensate for residual uncertainties in estimating performance.

## No Measure of Uncertainty Set in US Regulations

Neither EPA nor NRC set a numerical limit on the maximum uncertainty permitted (such as the spread in the dose results). In fact, in a response to comments suggesting that NRC specify an acceptable level of uncertainty, NRC replied in the preamble [7, p. 55748]:

> The approach defined in part 63, which requires DOE to fully address uncertainties in its performance assessment rather than requiring DOE to meet a specific level of uncertainty, is appropriate. The treatment of uncertainty in DOE's performance assessment will be an important part of NRC's review.

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[1] The generic health standard, 40 CFR 191, for mined geologic disposal first promulgated by EPA in 1985, and the corresponding implementing regulation, 10 CFR 60, promulgated by NRC, are still in force and could, in concept be applied to future repositories in the US. However, the evolution in the strategy adopted for the site-specific regulations for the proposed Yucca Mountain repository, first promulgated in 2001, would likely be adopted for future repositories. Specifically, NRC stated when promulgating 10 CFR 63 that the "generic Part 60 requirements will need updating" [7; 8]; furthermore, NRC has suggested that they would be similar to 10 CFR 63 [9; 10]

Consequently, there is no penalty for uncertainty; instead, uncertainty for those aspects of regulatory interest must be addressed, and displayed along with the mean dose such that NRC has a reasonable expectation that the licensee has “demonstrated the safety of the repository.” This approach is reasonable because a measure of acceptable uncertainty would likely need to be tied to the value of the dose in relation to the limit (i.e., large uncertainty about a mean dose that is far below the dose limit would likely engender less regulatory concern than small uncertainty about a mean value that is only slightly below the dose limit).

These concepts can be illustrated notionally as follows. If a waste management program reduced the overall inventory disposed in a repository (but kept the waste type, the thermal loads for the repository/package the same and the geologic variation and fluid flow uncertainty remained the same for the smaller repository[2]) then the dose would decrease but the overall uncertainty associated with a disposal system would not materially change (Figure E-1, Curves A and B). Yet, any uncertainty from scenarios, models or parameters associated with geologic disposal may be of less regulatory concern if the corresponding reduction in dose is far below the limit (Figure E-1, Curve B).[3]

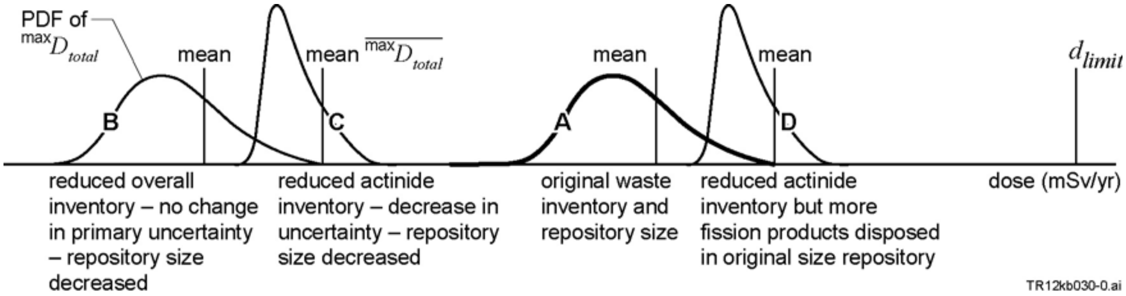

**Figure E-1. Possible changes in mean peak dose and uncertainty of the peak dose for a geologic disposal system when the radionuclide content of the disposed waste is changed. For Curves B, C, and D, the thermal loads and thermal constraints are assumed to be similar. Also, the geologic variation and fluid flow in the natural barrier is assumed to be similar.**

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[2] Because of the change in repository size, the uncertainty might not be the same in a highly heterogeneous geologic environment, but large heterogeneity is usually avoided in site selection. Furthermore, we are speaking of less than a factor of 10 decrease or factor of 2 increase in size. In the limit, as the repository size decreased to one package, spatial variability in an important parameter such as fluid flow at the package, for example, would disappear leaving only the spatial variability of corrosion rates on the one package. However, the underlying uncertainty in what value to use for fluid flow, for example, would still remain.

[3] The figure is plotting the probability density function (PDF) of the peak doses, whenever they occur over the regulatory period (~$10^6$ yr for Yucca Mountain repository). The *x*-axis is the individual dose (e.g., mSv/yr). The mean shown on the PDF is the expected value of these peak doses, regardless of time (i.e., $\mathcal{E}\{{}^{\max}D_{total}\}$). US regulations actually measure the mean of the dose over time, where the maximum of this measure must be less than the limit (i.e., ${}^{\max}\overline{D}_{total}(t) < d_{limit}$). The use of the PDF of peaks more readily shows the influence of uncertainty over the entire spectrum of behavior, since uncertainty as to when the peak dose occurs is of secondary importance.

The performance of waste from the current once-through open cycle can also be compared notionally with the performance of a waste from a theoretical, fully closed advanced fuel cycle. A closed fuel cycle would also produce in fission products and activation products as in the open cycle, but in the long-term, the inventory of uranium (U), plutonium (Pu), and minor actinides would be reduced to only quantities left behind in a less-than perfect separation process.[4]

For a closed, theoretical advanced fuel cycle that removes actinides, the situation might or might not be similar to reducing the inventory. If an actinide is a dominant contributor to dose, then the position of the mean dose would decrease similar to a reduction in overall inventory, possibly to a point that there is less regulatory concern. In addition, if a characteristic of an actinide is also important in causing the spread in dose results (e.g., uncertainty in retardation of the actinide), then its reduction would also reduce overall uncertainty (Figure E-1, Curve C).

If the removed actinide radionuclide is not a dominant contributor to dose, then the position of the mean dose would not change. Although a less common occurrence, in concept, some characteristic of an actinide radionuclide could still be important to causing the spread in the dose results about the mean without being a dominant contributor to dose. For this situation, the uncertainty and, thereby, the spread about the mean would decrease, but the decrease would be less, and usually much less, than if the actinide was an important contributor to dose.

## Radionuclides Important to Repository Performance

The focus of this report is on uncertainty of the dose performance measure. Two important components are the doses from the scenarios modeling (a) the undisturbed evolution of the repository, and (b) inadvertent human intrusion. The discussion of the third important component, dose from natural disturbance, is discussed in the section on characterizing scenario uncertainty.

### Undisturbed Performance

A general feature of geologic disposal systems is the role that geochemistry of the host rock and far-field groundwater plays in controlling radionuclide releases. The solubility of most actinides is a strong function of water chemistry of the groundwater (e.g., pH and reduction/oxidation conditions). In a reducing environment with fairly neutral pH (i.e., 6 to 9 pH, which are conditions expected in the salt, crystalline rock, and clay/shale environments located below the water table) actinides are very insoluble, which, in turn, leads to extremely small actinide releases from the disposal system. Reducing conditions also promote sorption of actinides and, hence, immobility in these three repository environments currently under study generically by the UFD Campaign [11].

As has been demonstrated by several studies [1; 2] and recent demonstration calculations by UFD [12], the hypothetical doses calculated for the undisturbed evolution of the crystalline rock and clay/shale repositories are dominated by doses from mobile fission products such as technetium and iodine ($^{99}$Tc and $^{129}$I) present in the repository for all fuel cycles, with usually no release from salt environments. Actinides such as neptunium and plutonium ($^{237}$Np, $^{239}$Pu, $^{240}$Pu) may contribute to dose but they are not the dominant source.

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[4] The Fuel Cycle Technology Program is currently studying a number of advanced fuel cycles. Categories include (1) open cycles with different fuel such as from high-temperature gas reactors; (2) modified open cycles that reprocess the open cycle fuel to produced mixed oxide fuel (MOX), which is then used once in a reactor and disposed; (2) thorium fuel cycles that significantly decrease minor actinides in the waste, and (3) fuel cycles that repeatedly recycle fuel in thermal spectrum reactors, which increases minor actinides. This study selected one at each end of the spectrum: the current open fuel cycle using light water reactors (LWRs) and a theoretical fully closed advanced fuel cycle using fast spectrum reactors with a maximum reduction of actinides in the waste.

For UFD demonstration calculations for a repository disposing 140,000 metric tons of heavy metal (MTHM) of commercial spent nuclear fuel (SNF) from a pressurized water reactor (PWR), the mean peak dose was $10^{-5}$ mSv/yr for mined geologic disposal in crystalline rock and $10^{-10}$ mSv/yr for deep borehole geologic disposal—doses which are many orders of magnitude below the limits set for US repositories (0.15 mSv/yr in the first $10^4$ yr or 1 mSv/yr thereafter) (Appendix A).

In other words, actinide removal would not materially decrease the individual dose for the undisturbed scenario of the repository. Whether removing actinides would bring about a reduction in uncertainty is discussed in later sections.

### Performance after Human Intrusion

Although numerous international studies have evaluated the influence of alternative fuel cycles on system performance for undisturbed conditions, the circumstances of human intrusion vary in the international community. Hence, results specific to the circumstances specified in the most recent US regulations are necessary. In a recent demonstration calculation by the UFD Campaign for a generic repository in crystalline rock, with properties similar to the proposed Swedish repository, the doses at a 5-km boundary are 5 orders of magnitude below the limit in the first $10^4$ yr for intrusion into a package containing 10 assemblies of commercial SNF [12]. Not only are doses far below the limit, but the mean annual dose is dominated by the $^{129}$I fission product.

For a generic repository in salt, with features similar to those of the Waste Isolation Pilot Plant (WIPP) in southern New Mexico, the mean peak dose at a 5-km boundary is 3 orders of magnitude below the limit after $10^4$ yr after intrusion into a package containing 10 assemblies of commercial PWR SNF. Although neptunium and plutonium actinides ($^{237}$Np and $^{239}$Pu) are the dominant contributors to the mean peak dose for the repository in salt, the doses are far below the limit; thus, any reduction in dose would not bring about a significant benefit.

## Influence of Fuel Cycles on Uncertainty and its Characterization

The goal of the waste management system is safe disposal as defined by the consensus expressed in EPA and NRC regulations. The goal is not to endlessly seek to reduce the estimated individual dose, which could be accomplished by developing numerous small repositories. Consequently, the waste management system may respond to a reduction in actinide inventory and corresponding heat load by disposing more radioactive waste in the same repository, if allowed by future social/political agreements for siting repositories. In this situation, mean peak doses might not decrease, but, instead, increase because of the increased amount of fission products, which typically dominate dose as noted above (Figure E-1, Curve D).

The question with respect to the performance of the disposal system is whether differences in inventory from an advanced fuel cycle will impact the uncertainty in radionuclide mobilization and migration to the accessible environment. Because the ultimate need for a geologic repository is independent of fuel cycle—fission products will need to be disposed—the issue reduces to evaluating the *incremental* decrease in scenario, model, or parameter uncertainty associated with not having to demonstrate to the NRC that Pu, uranium, and minor actinides will be isolated from the accessible environment for those aspects of regulatory interest.

In addition to evaluating whether removing actinides will provide an incremental decrease in uncertainty, removal of actinides may influence the degree of difficulty in characterizing uncertainty (i.e., screening FEPs, including processes in the models, and defining the parameter uncertainty). Hence, the impact on characterizing uncertainty is also discussed as relates to both the natural and engineers barriers of the disposal system. Because FEPs are a starting point for the evaluation of the dose measure, they are a convenient point to qualitatively evaluate the impact of advanced fuel cycles on the uncertainty.

## Characterizing Parameter and Model Uncertainty for the Natural Barrier

For the natural barrier of a geologic disposal system, a significant number of FEPs relate to the properties, behavior, and performance of the natural system with respect to its ability to retard or dilute the quantities of radionuclides that reach the accessible environment. For the purpose of evaluating the possible incremental decrease in uncertainty caused by removing actinides, those FEPs that are typically included in the performance assessment can be aggregated into three categories:

(1) Stratigraphic, mechanical, and hydrologic properties of the natural system

(2) Hydrologic processes of flow through the natural system

(3) Geochemical and transport processes influencing (a) dissolved radionuclide transport, (b) complexation with carbonates and organics, (c) sorption, and (d) colloid facilitated transport

Other FEPs must also be considered but are typically excluded when modeling behavior of the natural barrier system (NBS) related to

(4) Biological processes

(5) Nuclear criticality

Finally, some FEPs are important at the interface with the engineered barrier system (EBS) [5] but their influence on movement of radionuclides through most of the natural barrier is generally excluded related to

(6) Thermal processes

(7) Gas sources

Three aspects of FEPs are pertinent here: (a) the impact on the technical basis to include or exclude a FEP in models of the disposal system for the analysis; (b) the effort to include the FEP in the modeling system and its impact on modeling uncertainty; and (c) the effort to characterize the parameter uncertainty related to a FEP if it is included in the analysis. The uncertainties associated with the first two categories (properties and hydrologic processes) are unchanged by the removal of actinides: the model components are developed, and the parameter uncertainties are characterized and propagated, regardless of the fuel cycle. For the third set (geochemical and transport processes), advanced fuel cycles that removes radionuclides from the disposed wastes would reduce somewhat the characterization of parameter uncertainty necessary for dissolved radionuclide transport and sorption because it may not be necessary to include those radionuclides in the performance assessment. Yet, the effort to characterize uncertainty is

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[5] As defined by the NRC [7], the "*engineered barrier system* means the waste packages, including engineered components and systems other than the waste package, and the underground facility" where the "*waste package* means the waste form and any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container" and where "*underground facility* means the underground structure, backfill materials, if any, and openings that penetrate the underground structure (e.g., ramps, shafts, and boreholes, including their seals)." In this report, however, we have included most of the thermally perturbed portion of the host rock with the EBS (e.g., 100 m around a disposal borehole) to avoid tedious repetition of factors related to the natural barrier and EBS, and placed the waste form in its own category to focus attention on alternative forms.

not completely eliminated. FEP exclusion arguments, based on some type of limited characterization, would still have to be made showing that the very small amounts of actinides and other radionuclides remaining from a less than perfect separation process are not important to the performance assessment.

Conceivably, the reduced characterization and reduced conceptual model uncertainty for colloid-facilitated transport using advanced fuel cycles could be important. Actinides are susceptible to transport by attaching onto mobile colloid particles. Since actinides are highly sorbing and sparingly soluble under most conditions anticipated in a geologic disposal system, colloid-facilitated transport can lead to farther, faster migration for a portion of the actinides than would otherwise be expected. It follows that a fuel cycle that reduces the quantity of actinides in a repository through partitioning and transmutation might reduce uncertainties in processes associated with colloid-facilitated transport.

However, an important factor argues against this conceptual model uncertainty having a strong influence on the spread of the results and, thereby, being an important consideration in judging whether an advanced fuel cycle influences the overall uncertainty of a geologic disposal system. As already noted, dose is dominated by mobile, long-lived fission products in chemically-reducing repository environments of salt, crystalline rock, and clay/shale repositories. Hence, the propagation of uncertainty associated with less mobile actinide radionuclides will be muted, and possibly unimportant, in relation to the overall spread of the dose results. The modeling at Yucca Mountain and experiences at other sites contaminated with actinides support this conclusion, as discussed in a later section.

## Characterizing Parameter and Model Uncertainty for the Engineered Barrier

As with the natural barrier, three aspects of FEPs related to the uncertainty associated with the engineered barrier system (EBS) (excluding the waste form in this section) are pertinent here: (a) the impact on the technical basis to include or exclude a FEP in models of the disposal system for the analysis; (b) the effort to include the FEP in the modeling system and its impact on modeling uncertainty; and (c) the effort to characterize the parameter uncertainty related to a FEP if it is included in the analysis.

Four broad categories of FEPs are usually included, and corresponding modeling components developed for the EBS:

(1) EBS integrity including (a) waste package degradation, (b) degradation of buffer/backfill/seals and other materials of EBS, (c) biological processes enhancing degradation of EBS components; and (d) mechanical processes influencing EBS performance

(2) Hydrologic processes impacting the EBS

(3) Geochemical and transport processes influencing movement of radionuclides through the EBS, including (a) conditions of water entering the EBS; (b) radionuclide speciation and solubility, (c) complexation with carbonates and organics, (d) sorption, and (e) colloid transport

(4) Thermal effects on EBS components

A major difference between the EBS and natural barrier is the importance of FEPs related to thermal processes, because of the proximity of the EBS components to the heat-generating waste.

One FEP category depends upon the repository environment with the very impermeable clay/shale and salt repositories possibly including the effects, and with crystalline repositories usually excluding the FEP category:

(5) Non-radiological gas sources from anoxic corrosion of metal components, or microbial degradation of organic material

Finally, other categories that must be considered but are usually excluded from the performance assessment include

(6) Radiation effects and nuclear criticality in the EBS.

FEPs related to (4), thermal effects on EBS components, must be included and parameters characterized because the influence of advanced fuel cycles on thermal output of the SNF versus high-level waste (HLW) is large. However, the overall repository temperature peaks and the uncertainty associated with these peaks caused by thermal effects would likely remain unchanged. To elaborate, uncertainty related to thermal effects is typically limited setting design constraints on thermally sensitive components of the disposal system. These design constraints result in uncertainty from thermal effects that can be tolerated, as confirmed through experiments and modeling of the coupled thermal-hydrologic processes. That is, if a component of the disposal system (such as waste form, package, or geologic medium) degrades rapidly or changes properties above a certain temperature threshold, then a thermal constraint (such as on peak package and peak host rock temperatures) can be established with an appropriate safety margin. These constraints are established by, for example, using the worse-case design basis heat load for the wastes and bounding thermal properties. An engineering strategy, such as minimum acceptable waste package and drift spacing, can then be adopted such that the repository does not exceed the thermal design constraints.

As already noted in relation to Figure E-1, a likely response of the waste management system to a reduction in the inventory of heat generating actinides would be to increase waste loading and/or reduce waste package spacing for the repository design in order to approach previously established thermal design constraints if allowed by future social/political agreements. For example, HLW packages may be made much hotter initially than either SNF or the current defense HLW in the US. Provided the various thermal design constraints are met with similar margins of safety, it follows that the performance of a repository will be similar in relation to degradation of the packages, performance of the buffer, and behavior of the near field. It also follows that any scenario, model, or parameter uncertainty associated with thermal behavior of the repository would be similar. Rather, the influence of an advanced fuel cycle would be primarily on the cost to the waste management system to meet the thermal design constraints relative to other engineering strategies that influence thermal behavior, such as surface storage cooling, amount of waste in each package, repository layout, and amount of waste disposed in a single repository (if area is constrained).

No change in modeling uncertainty or characterizing parameter uncertainty would occur for FEPs related to (1a) waste package degradation; (1b) degradation of other EBS components; and (1c) biological processes enhancing degradation of EBS components. These FEPs must still be modeled and the same parameters characterized whether actinides are present or not. Mechanical impact of internal pressurization by gas produced by actinides (1d) might have an influence on packages that to do not degrade first from other processes, but typically this process is excluded even when actinides are included in the waste, for repository environments with sufficient advective flow such as crystalline rock repositories. Certainly, reasons for excluding this FEP and FEPs related to (6), radiation effects and nuclear criticality, would be simpler without the presence of actinides.

Modeling of FEPs and characterization of parameter uncertainty related to (2), hydrologic processes of flow through the EBS, would be unchanged by the removal of actinides. Also, characterizing uncertainties and including fission products in models will still be necessary for FEPs related to (3), geochemical and transport processes influencing movement of radionuclides through the EBS, except for FEPs related to colloid-facilitated transport, as discussed for the natural system. Furthermore, arguments for excluding the actinides left from the less than perfect separation process would still require some characterization, as previously mentioned. Certainly, the results from modeling these two categories of FEPs are influenced by the temperatures of the waste form; however, only the time at which these hydrologic processes become important will be influenced by different decay histories with and without actinides. The FEPs must still be included, and parameters characterized, with or without the presence of actinides.

## Characterizing Parameter and Model Uncertainty for the Waste Form

Four broad categories of FEPs (many similar to the EBS) are usually included and corresponding modeling components developed, for the waste form:

(1) Inventory of actinide and fission product activity

(2) Degradation related to (a) commercial SNF waste form and cladding degradation, (b) HLW degradation and (c) enhanced degradation through biological processes

(3) Thermal processes related to waste form degradation

(4) Geochemical and transport processes related to (a) in-package chemistry, (b) radionuclide speciation and solubility, (c) complexation with carbonates and organics, (d) sorption, and (e) colloid stability and transport

One FEP category depends upon the repository environment with the very impermeable clay/shale and salt repositories possibly including the effects, and with crystalline repositories usually excluding the FEP categories (similar to the situation for non-radiological gas sources in the repository/package component of the EBS):

(5) Gas sources from fission products and helium from alpha decay of actinides

Finally, another category that must be considered but is usually excluded from the performance assessment includes

(6) Radiation effects

An advanced fuel cycle with actinide partitioning and transmutation would reduce somewhat the characterization of parameters uncertainty necessary for (1), inventory, and geochemical and transport processes related to (4a) in-package chemistry, (4b) solubility, (4c) complexation, and (4d) sorption, because parameters for actinides would not be present. However, arguments for excluding the actinides left from the less than perfect separation process would still require some characterization, as previously mentioned. Also, it would not eliminate the need for these modeling components because fission products would still be present.

The modeling of (2c), enhanced degradation from microbial activity, would not be materially influenced by the fuel cycle. Similarly, (3), thermal effects on waste form degradation, would likely be similar because the same thermal constraints on the repository design are observed, as previously discussed for the EBS.

Modeling components for (4e), formation and stability of colloids for colloid facilitated transport of actinides within the EBS, would not be necessary in the absence of actinides, as discussed for the natural barrier. Similar to the situation for the EBS, the arguments for excluding (6), radiation effects from alpha decay on waste form degradation, would be simpler without actinides present.

Regarding FEPs related to waste form degradation, potentially, a HLW waste form offering better performance relative to borosilicate glass or zircaloy-clad SNF could be developed as part of the current open fuel cycle or a future advanced fuel cycle. However, new waste forms do not always produce substantially better disposal system performance. As observed in UFD demonstration calculations for clay/shale repository environments and at Yucca Mountain in the oxic environment (Appendices A and D), other components of the multiple barrier disposal system compensate for less favorable characteristics of the borosilicate glass or zircaloy-clad SNF. Furthermore, new waste forms require extensive characterization of uncertainty, which would increase the burden, at least initially, rather than decrease the burden, especially for advanced fuel cycles that produce multiple waste streams and multiple waste forms.

In general, flexibility in accommodating various waste forms has been an intended attribute of geologic disposal system designs, rather than finely tuning the disposal system to specific characteristics of the waste. Flexibility is a natural outcome of using multiple barriers in the geologic disposal system. For example, current geologic disposal systems have been designed for a variety of waste forms: direct disposal of SNF only (Sweden in crystalline rock), for HLW only (France in clay/shale), and for a mixture of SNF and HLW (US in volcanic tuff [13]).

## Characterizing Scenario Uncertainty

For developing natural disruptive scenarios, the general categories of external agents acting upon the disposal system are geologic, climatic, and planetary (Appendix C). Planetary events include meteorite impact, changes in the earth's magnetic field, and solar flares. Climatic changes include natural variations in precipitation and temperature as well as glacial effects. For planetary and climatic types of external agents, the event probability dominates the dose. Because a change in actinide inventory would have no influence on the uncertainty of the event, the spread of the results about the mean could not be changed significantly.

Geologic agents include (1) long-term processes such as dissolution and tectonic activity causing uplift, subsidence, faulting, or folding; (2) igneous activity, and (3) seismic activity. Again, the event probability dominates the dose; thus, a change in actinide inventory would not have any influence on the uncertainty of the event, and so the spread of the results would not be changed significantly. The scenario uncertainty for geologic agents depends on the timing and the number of events, which are site-specific. Initially the frequency and severity of a natural disturbance would be addressed during site selection; later, they would be addressed during site characterization. Because a generic approach cannot easily evaluate specifics as to the frequency and severity for a non-specific location, and because actinides cannot influence scenario uncertainty, it is not discussed further except for secondary effects.

A secondary effect may occur in that a natural or anthropogenic disturbance scenario causes a change to occur in the configuration of the disposal system. For inadvertent human intrusion, the change in the disposal system configuration involves a fast path in the natural system. However, EPA and NRC did not identify fast paths that bypassed features of the natural barrier system as of regulatory interest.[6] Rather, disruption to the EBS was the influence of most regulatory interest. A change in configuration, in turn, may make other radionuclides such as actinides more important, in which case, a reduction in actinide inventory would reduce the dose. However, the uncertainty would not likely change except in the manner already described for the undisturbed scenario, because parameters of the natural barrier have such an important influence on the uncertainty in the dose as described below.

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[6] An exception is an igneous event that erupts the contents of several packages into the atmosphere [14]. For this scenario, actinides are a dominant contributor to dose, but doses are far below the regulatory limit [15, Fig. 8.2-10].

## Uncertain Scenarios and Parameters in Real Disposal Systems

Although much can be learned from the behavior of generic disposal systems, the uncertainty of a generic disposal system is arbitrarily defined for modeling purposes. Only a real disposal system has uncertainty that must be discerned through characterization. Several results from the proposed Yucca Mountain are pertinent. As regards the contribution of various scenarios and thereby scenario uncertainty to total dose, the doses from the undisturbed scenario were the most important contributor to the total dose in early iterations of performance assessments. For the undisturbed scenario without inclusion of disruptive events, mobile fission products $^{99}$Tc and $^{129}$I were the most important contributors even in an oxic environment.

As understanding of the Yucca Mountain disposal system increased, the peak doses generally decreased from those calculated initially. Coincident with the general decrease in peak doses, there was a general increase in the contribution of the dose from natural disruptive events, especially igneous disruption. While the radionuclides contributing to total dose from seismic events (a scenario that damaged the EBS) were $^{99}$Tc and $^{129}$I fission products, the dramatic disruption of the EBS caused by the igneous event increased the importance of actinides. Interestingly, the igneous event at Yucca Mountain remained at the threshold of being excluded from the analysis based on the regulatory criterion (an annual probability of $2 \times 10^{-8}$ for the igneous event is only slightly larger than minimum regulatory criterion of $10^{-8}$). Consequently, the doses calculated were near the threshold of regulatory concern.

In the sensitivity/uncertainty analysis conducted for the Yucca Mountain disposal system, uncertain parameters of the natural barrier system (which are parameters unrelated to the fuel cycle), most often showed up as important in explaining the spread of the results about the mean dose (e.g., percolation in the unsaturated zone and fluid flux in the saturated zone were always important). As the EBS desing evolved, corrosion resistance of the waste package was increased, and a few parameters related to the package robustness become the most important (but these parameters are also unrelated to the fuel cycle). Uncertainty in natural parameters such as biological dose conversion factors directly related to $^{99}$Tc and $^{237}$Np and uncertainty of parameters for the waste form such as the solubility of U and Pu were somewhat important but ranked at the end of the list of important parameters (Appendix B).

The performance assessment of the Yucca Mountain disposal system also considered colloid-facilitated transport for several actinides. The solubility of actinides and stability of colloids at the location of the waste form were generally very low. Furthermore, the concentration of groundwater colloids, another parameter directly influencing colloid-facilitated transport, was only of moderate importance in explaining the spread of the dose about the mean. In reducing environments and environments with limited advective water flow (e.g., clay and salt), this result would be even more pronounced.

The experience of actinide transport at other sites contaminated with radionuclides supports the finding at Yucca Mountain. Risk assessments at sites such as Hanford, Los Alamos National Laboratory, Nevada National Security Site (formerly called the Nevada Test Site), and the Savannah River Site show dissolved radionuclides dominating the total dose. The Rocky Flats site dealt extensively with the issue of plutonium transport, and eventually analysts dismissed colloid-facilitated transport. In other words, observations indicate that while very small quantities of actinides, present in colloidal form, may travel a considerable distance, the vast majority of the actinide inventory remains very close to the source, as expected for a relatively immobile constituent.

## Summary of Key Points

For the undisturbed scenario, the natural barrier system in reducing environments, coupled with the engineered barrier system, greatly reduces the mobility of actinides, such that fission products, which exist in all fuel cycles, dominate the hypothetical dose to individuals $10^4$ to $10^6$ yr in the future. Hence, removal of actinides from the repository would not change the magnitude of the mean dose.

For disruptive scenarios, changes in actinide inventory cannot change the inherent uncertainty of the event, but as a secondary effect, extensive disruption of the engineered barrier system can result in more actinide releases. Although dose might decrease somewhat with the removal of actinides, the probability-weighted dose is already so small for inadvertent human intrusion, and possibly for natural disruptions as well, that use of an advance fuel cycle to further decrease these already insignificant doses would not be warranted.

Because geologic disposal is required for fission products regardless of the fuel cycle, the issue of importance is whether removing actinides provides a noticeable *incremental* decrease in the spread (uncertainty) of dose. However, the spread of dose is usually caused by parameters unrelated to the characteristics of actinides; specifically, parameter uncertainty associated with the natural barrier. In addition, a few parameters of the waste package of the engineered barrier system can contribute to the spread of the dose, (particularly in disposal environments in which advective releases provide an important contribution to total dose).

Processes and associated parameters directly related to actinides have only a weak influence on the spread of the dose. The most obvious process is colloid-facilitated transport of actinides, but because actinides are not the primary contributors to dose in most environments, the uncertainty associated with colloid-facilitated transport of actinides is muted. Furthermore, any remaining uncertainty specifically associated with fission products is not necessarily less than the uncertainty associated with actinides. Hence, the spread of dose results will not be significantly reduced by the removal of actinides in the inventory.

The engineered barrier system design would likely change (repository area reduced and/or container capacity increased) to meet previously established design constraints on thermally sensitive components for waste produced by an advanced fuel that has lower thermal output. Hence, any scenario, model, or parameter uncertainty associated with thermal behavior of the repository would be similar, provided the thermal design constraints are met with similar margins of safety with and without the presence of actinides. Rather, the influence of an advanced fuel cycle would be primarily on the cost to the waste management system to meet the thermal design constraints relative to other engineering strategies that influence thermal behavior, such as surface storage duration, waste package capacity, repository layout, and repository capacity (if area is constrained).

The characterization of natural and engineered barrier uncertainty is a major task of a performance assessment for a geologic repository. This task remains a major effort regardless of the fuel cycle. Granted, parameter characterization and modeling components for formation, stability, and transport of colloids would be unnecessary in the absence of actinides. Also, removal of actinides would somewhat diminish the characterization of parameter uncertainty related to inventory, solubility, and sorption because of their absence, but some characterization would be necessary to support screening out the importance of remnant actinides in the less than perfect separation. Furthermore, the modeling components would still be necessary and the associated modeling uncertainty would still be present for the fission products.

Any of the small benefits of reducing uncertainty from actinide removal described above would potentially be offset by the need to characterize new waste forms (either HLW or advanced fuels). As an example, in the case of HLW disposed in a new ceramic waste form, the applicant under the Yucca Mountain regulations (10 CFR 63) (and presumably future regulations) would need to (a) “provide the technical basis for either inclusion or exclusion of features, events, and processes” on various modes of failure and degradation. (b) “consider alternative conceptual models” that explain modes of degradation, and (c) “account for uncertainties and variabilities in parameter values” for the mathematical models developed for the performance assessment.

Furthermore, any of the small benefits of actinide removal would only be realized in the situation where current nuclear fuel from the open cycle is stored and then fully reprocessed when an advanced fuel cycle with actinide partitioning and transmutation is fully implemented in the future. Any transition period in which one or more repositories are built to handle SNF and HLW from the open cycle or a transition open cycle would necessitate the characterization of uncertainty and inclusion of modeling components related to actinides.

Therefore, the UFD Campaign can reasonably conclude that advanced fuel cycles, in combination with partitioning and transmutation, which remove actinides or that use advanced fuels, will not significantly alter (1) the repository performance, (2) the spread in dose results around the mean, (3) the modeling effort to include significant FEPs in the performance assessment, or (4) the characterization of uncertainty associated with natural or engineered barriers of a geologic disposal system in the regulatory environment of the US. This finding ultimately rests on the fact that the influence of uncertainty in waste form behavior is diminished because other barriers often control the release, whether by design in the case of a robust waste package or by existing geochemical conditions in the natural barrier. In other words, the combination of the natural and engineered barriers provides a geologic disposal system that mitigates the unknowns of scenario uncertainty and model uncertainty and provides sufficient flexibility to accommodate a large variety of radioactive wastes from existing commercial reactors, experimental reactors, and reprocessed fuel from future fuel cycles.

However, as the Fuel Cycle Technology Program pursues the development of sustainable fuel cycles, the UFD Campaign should continue to anticipate that nuclear fuel cycles that remove short-lived, heat-producing radionuclides and long-lived actinides will have a significant impact on the engineered barrier of a repository (e.g., layout and waste package spacing), waste package (volume and heat load) as well as the overall waste management system (influencing, for example, surface storage duration).

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# ACRONYMS

| | |
|---|---|
| ATR | Advanced Test Reactor |
| BDCF | Biological Dose Conversion Factor |
| BRC | Blue Ribbon Commission on America’s Nuclear Future |
| CCDF | Complementary Cumulative Distribution Function |
| CEDE | Committed Effective Dose Equivalent |
| DOE | Department of Energy |
| DSNF | DOE-owned spent nuclear fuel |
| EBS | Engineered Barrier System |
| EC-Ceramic | Electrochemical-Ceramic HLW waste form |
| EC-metal | Electrochemical-metallic HLW waste form |
| EDZ | Excavation Disturbed Zone |
| EPA | Environmental Protection Agency |
| FCT | Fuel Cycle Technology |
| FEP | Features, Events, and Processes |
| FP | Fission Product |
| GDS | Generic Disposal System |
| GW | Groundwater |
| HLW | High-Level Waste |
| HTGR | High-Temperature, Gas-Cooled Reactor |
| IRG | Interagency Review Group |
| LA | License Application |
| LILW | Long-Lived Low- and Intermediate-Level Waste |
| LLNL | Lawrence Livermore National Laboratory |
| LL | Long-Lived |
| LLW | Low-Level Waste |
| LWR | Light Water Reactor |
| MA | Minor Actinide |
| MOX | Mixed Oxide |
| MTHM | Metric Tons of Heavy Metal |
| NAS | National Academy of Sciences |
| NBS | Natural Barrier System |
| NEA | Nuclear Energy Agency |
| NRC | Nuclear Regulatory Commission |
| OECD | Organisation for Economic Co-Operation and Development |
| P&T | Partitioning and Transmutation |
| PA | Performance Assessment |
| PDF | Probability Density Function |
| Pu | Plutonium |
| PWR | Pressurized Water Reactor |
| R&D | Research and Development |
| RMEI | Reasonably Maximally Exposed Individual |
| SCC | Stress Corrosion Cracking |
| SiC | Silicon Carbide |
| SKB | Swedish Nuclear Fuel and Waste Management Company |
| SL | Short-Lived |
| SNF | Spent Nuclear Fuel |
| SNL | Sandia National Laboratories |
| SR | Site Recommendation |

| | |
|---|---|
| Sv | Sievert |
| SZ | Saturated Zone |
| TRISO | Tri-Structural Isotropic |
| TRU | Transuranic |
| TSPA | Total System Performance Assessment |
| TWh | Terawatt hour |
| U | Uranium |
| UFD | Used Fuel Disposition |
| UNF | Used Nuclear Fuel |
| UOX | Uranium-Dioxide |
| US | United States |
| UZ | Unsaturated Zone |
| VA | Viability Assessment |
| WIPP | Waste Isolation Pilot Plant |
| WP | Waste Package |
| YMP | Yucca Mountain Project |

## USED FUEL DISPOSITION CAMPAIGN

# INFLUENCE OF NUCLEAR FUEL CYCLES ON UNCERTAINTY OF LONG-TERM PERFORMANCE OF GEOLOGIC DISPOSAL SYSTEMS

# 1. INTRODUCTION

## 1.1 Objective

One of the missions of the Fuel Cycle Technology (FCT) Program of the United States (US) Department of Energy (DOE) Office of Nuclear Energy is to “Develop sustainable fuel cycle technologies and options that improve resource utilization and energy generation, reduce waste generation, enhance safety, and limit proliferation risk.” Development and implementation of advanced fuel cycle technologies, including partitioning and transmutation, will impact storage, transportation, and disposal in the waste management system. This report by the FCT Used Fuel Disposition (UFD) Campaign evaluates the impact of advanced fuel cycles on one aspect of the waste management system, uncertainties associated with geologic disposal.

### 1.1.1 Measures of Impact on Geologic Disposal System

In an international review of the impact and benefits of alternative fuel cycles with partitioning and transmutation (P&T), the Nuclear Energy Agency (NEA) Organisation for Economic Co-Operation and Development (OECD) noted that the impact of advanced fuel cycles including P&T was somewhat ambiguous:

> Despite a very large number of studies, both at national and international levels, there is not a general consensus on the impact of such P&T strategies on the repository performance, caused partly by the use of different repository environments and partly by the repository performance analysis approach and assumptions.

To deal with this ambiguity, this report focuses on the potential influence of advanced fuel cycles on the uncertainty of repository performance in the regulatory environment of the US.

The primary manner that an advanced fuel cycle will influence a geologic disposal system is through the (1) radionuclide inventory of the waste, (2) the heat output of the waste; (3) the amount of volume and mass of the waste, and (4) the form of the waste. The influence of the changes in waste radionuclide inventory, amount, and waste form on the geologic disposal system may be measured in several ways: (1) an indicator of cost as measured by area of the repository and size and number of packages from volume, mass, and decay heat of waste; (2) an indicator of proliferation resistance; and (3) an indicator of safety performance of the repository as measured by the peak of the mean individual dose over a regulatory time period. Proliferation resistance is beyond the scope of this report, and measures of repository capacity will only be discussed tangentially.

As further described in the following chapter, there is no indicator selected or measure developed for the concept of uncertainty in the US. Rather, the uncertainty associated with geologic disposal must be included in the evaluation of the individual dose performance measure. Hence, while uncertainty is the primary focus of the report, the report also discusses the dose measure to some degree.

## 1.2 Approach

As described in the next chapter, geologic disposal analysis typically groups the numerous sources of uncertainty into three large categories: parameter uncertainty, model uncertainty, and scenario uncertainty. The technical basis for inclusion or exclusion of specific features, events, and processes (FEPs) is an important part of scenario uncertainty. Because FEPs are a starting point for the evaluation of the dose measure, they are a convenient point to qualitatively evaluate the impact of advanced fuel cycles on the uncertainty. Three aspects of the evaluation are pertinent here: (1) the impact on the technical basis to include or exclude a FEP in the analysis; (2) the effort to include the FEP in the modeling system; and (3) the effort to characterize the parameter uncertainty related to a FEP in the analysis.

### 1.2.1 Influence of Two Generic Nuclear Fuel Cycles Discussed

In general, efforts to employ recycling and reprocessing methods are designed to make better use of the used nuclear fuel (UNF),[7] thereby stretching the uranium (U) resource and transmuting the actinides produced in the original fission reactors to produce faster decay radionuclides. The Fuel Cycle Options Campaign is currently studying a number of fuel cycles. The UFD Campaign selected one fuel cycle of each of three primary types as representative for use in repository studies: Open, Modified Open, and Closed Fuel Cycle options. These fuel cycles are similar to those considered by the Blue Ribbon Commission (BRC) on America's Nuclear Future [16, p. 102]. From these three, two are discussed

1. Once-through open cycle using light water reactors: In the once-through open cycle, currently used by all light water reactors (LWRs) in the US and much of the world, uranium-dioxide (UOX) UNF is stored on-site at the reactor in either wet pools or in dry storage casks. The UNF might be moved to centralized extended storage prior to disposal, but for the once-through-cycle, the UNF is considered spent nuclear fuel (SNF) to be eventually directly disposal in a geologic repository.

2. Closed fuel cycle using fast reactors: The closed fuel cycle with fast reactors is a theoretical cycle that maximizes use of uranium resources, eventually eliminating the need for uranium enrichment, disposes of high-level waste (HLW) from reprocessing SNF, and minimizes the amount of actinide disposal. This cycle might generate a new-extraction borosilicate HLW glass, electrochemical separation HLW ceramic, and/or electrochemical separation HLW metal, all containing fission products

In the long term, a fully closed fuel cycle would result in a large decrease in the quantity of actinides in the waste forms requiring geologic disposal. Although all of the fission products still exist and require disposal, actinide inventories are reduced to the quantities that are left behind in a less-than-perfect separation process. Radioactive wastes from a fully closed fuel cycle could have a greater than 99% reduction in the quantities of plutonium (Pu), neptunium (Np), and other minor actinides than the open fuel cycle, when normalized to the same amount of electricity generated. Although not restricted to closed fuel cycles, the waste management system might also tailor the waste form to offer better performance relative to borosilicate glass or zircaloy-clad SNF.

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[7] In current usage, the term "used fuel" or "used nuclear fuel" is applied to fuel that has been irradiated in a reactor and withdrawn but for which no decision has been made about whether it will be reprocessed to recover usable radionuclides or disposed directly. This report discusses waste management options for UNF for which presumably the decision has been made either to directly dispose as spent nuclear fuel (SNF) or to process to recover usable uranium (U) and plutonium (Pu), further burn (transmute) actinides (e.g., neptunium, $^{237}$Np), and dispose of the remaining fission products (e.g., technetium, $^{99}$Tc, iodine, $^{129}$I, cesium, $^{135}$Cs and $^{137}$Cs, and strontium $^{90}$Sr) as high-level waste (HLW).

The third type of fuel cycle occasionally considered by the UFD Campaign is,

3. Modified open cycle using mixed oxide (MOX) fuel in light water reactors. In the modified-open cycle, LWR UOX is reprocessed to produce a uranium/plutonium (U/Pu) mixture that is then directly fabricated into a MOX fuel that is subsequently used once (not recycled). The waste is MOX SNF and HLW in the form of borosilicate glass from reprocessing of the UOX fuel. The MOX fuel cycle is the only alternative fuel cycle currently used in the world (France, Germany, Switzerland, Belgium, and Japan). The US is building a MOX fuel fabrication facility in South Carolina to process ~50 metric tons of heavy metal (MTHM) of excess defense Pu waste.

Although the modified-open fuel cycle may be important for transitioning to other advanced fuel cycles, it is not seen as a long-term fuel cycle and, thus, is not discussed further here.

There is a range of additional advanced fuel cycles that could be considered, but do not need examination in this report. Two examples are fuel cycles using thorium fuel and fuel cycles that could increase minor actinide content in waste rather than reduce it. Thorium fuel cycles, which are breeding cycles, result in HLW similar to HLW from reprocessing UOX UNF, but with significantly less minor actinide content and somewhat different distribution of fission products. The reduction in minor actinides is similar to the actinide removal for uranium fuel cycles, which is considered in this study. The different distribution of fission products changes some details of the long-term dose evaluation, but not the fundamental requirement for repository performance [5, p. 10]. Also, some proposed fuel cycles increase minor actinide production because of repeated reprocessing of the Pu component of the waste in thermal spectrum reactors such as LWRs. Because this increase is minor (a factor of 2 to 3 increase) compared to the potential actinide reduction in fuel cycles that promote transuranic (TRU) transmutation (1 – 2 orders of magnitude decrease), these cycles would not be significantly different as relates to disposal of fuel from the reference once through open cycle case considered here.

### 1.2.2 Four Types of Geologic Disposal Considered

A disposal system (or geologic repository in 10 CFR 63 [7, §63.2 ]) is defined as the combination of engineered and natural barriers systems (NBSs) within the controlled area that isolate radioactive waste after disposal [6, §197.12; 17, §191.12]. The components of the engineered barrier system (EBS) include the waste package and the underground facility. The waste package includes the waste form, waste container, and any backfill immediately surrounding the waste container.

Currently, the UFD Campaign is investigating four main disposal environment options in a generic sense: mined repositories in three geologic media (salt, clay/shale, and granite) and the deep borehole concept in crystalline rock [11]. For each of these disposal options, the rock type is identified at a broad level. Salt includes both bedded and domal rocks; clay/shale includes a broad range of fine-grained sedimentary rocks including shales and claystones as well as soft clays; and granite includes a range of related crystalline rocks.

Salt, clay/shale, and crystalline rocks are the most frequently considered geologic media in the international community. Crystalline repository concepts have been evaluated in Switzerland and Japan. Sweden and Finland have selected crystalline sites and are undergoing regulatory review required before repository construction. Clay/shale disposal concepts have been evaluated in France, Belgium, and Switzerland. Finally, Germany continues to investigate disposal of heat-generating SNF and HLW in salt.

Salt, clay/shale, and crystalline rocks represent a reasonable cross-section of behavior. Salt and clay/shale represent sedimentary rocks with different degrees of strength, cavity-stability, mining experience, heat resistance, thermal conductivity, and radionuclide adsorptive behavior in which the disposal environment is reducing, remains anoxic, and the releases under undisturbed conditions are dominated by diffusion.

Crystalline rocks represent igneous or metamorphic rocks that differ from salt and clay/shale in deformation behavior/strength, the greater importance of the package to the disposal system performance, and the usual lack of desirable hydrocarbons in close proximity and, thus, absence of boreholes and their associated hazards. The repository environment in deep crystalline rocks is typically reducing and remains anoxic, but radionuclide release can be dominated by advection. Crystalline rocks are also the primary basement rock to consider for deep borehole disposal; however, in deep boreholes, diffusion is the dominant release mechanism except for an initial period of thermally driven advective flow. Although the focus of this report is on reducing conditions in anoxic repository environments, we report findings related to the uncertainty associated with Yucca Mountain (Appendix B), in which the repository environment is oxic, and releases are diffusion dominated at early times but transition to advectively dominated releases at late times, because of the US extensive experience with volcanic tuff.

## 1.3 Background

### 1.3.1 2009 and 2010 Fuel Cycle Options Studies

As part of the mission to develop fuel cycles that improve resource use, improve energy generation, reduce waste, enhance safety, and limit proliferation risk, the FCT Program conducted a fuel cycle options study in two phases in 2009 and 2010. Phase I reviewed and summarized possible fuel options, identified issues associated with nuclear power, and developed indicators and measures for each issue [4]. Phase II grouped the issues into five categories and identified fuel cycle options that would have a significant beneficial impact on the issues [5]. The five issues were [18] (1) nuclear waste management, (2) proliferation risk and security, (3) safety, (4) sustainability, and (5) economics. For nuclear waste management, the measures were mostly related to disposal: peak dose, radiotoxicity, mass of UNF, HLW, and low-level waste (LLW), the material heat load, and decay impact on length of interim storage and capacity. The study concluded that modifications to the current once-through open fuel cycle and modified open transitional fuel cycles would not have significant beneficial impact. Only the theoretical closed fuel cycle using fast reactors to completely consume all actinides (transuranic, TRU, radioisotopes) would have a significant beneficial impact; specifically [18]:

> Continuous recycle appears to be the only practical fuel cycle strategy that can significantly affect waste management issues for UNF and HLW, but only if all of the TRU is recycled, leaving only fission products and residual amounts of TRU in the HLW.

Although not a specific measure related to the waste management, the Option Studies did discuss the perceived impact of the closed fuel cycle on the uncertainty related to undisturbed and disturbed performance of a geologic disposal system. The Options Studies observed that in some repository environments dose is dominated by disruptive events. In order to reduce the importance of scenario uncertainty caused by disruptive events one might reduce toxicity of the waste by reducing the actinide content; specifically [18, p. 39],

> With respect to disturbances, it appeared that the risk from disposal may be reduced by reducing the actinide inventory in the repository to reduce both actinide elements and their decay products (an action important for either uranium or thorium use), although in some cases it would be beneficial to reduce the inventory of certain fission products as well. While this could be accomplished by reducing the planned capacity of a repository, either complete consumption of the fuel or recycle of the actinide elements was seen to provide a significant benefit. However, it was also observed that there is subjectivity to the analysis of disturbed events, especially for the assumptions made as to the nature and consequences of the disturbance, and uncertainty is high for predicting future events. Reduction in inventory lessens the importance of these uncertainties in an overall assessment of the repository capabilities…It was observed

> that analysis of undisturbed performance may also be partly subjective due to assumptions that are made, but in general there appeared to be less uncertainty about performance for undisturbed conditions.

This theme of reducing uncertainty related to disruptive events, in general, and human intrusion, in particular, by reducing the toxicity of the waste through removal of actinides would be echoed by an NEA review study completed in 2011.

### 1.3.2 2011 Nuclear Energy Agency Review of Previous Studies Evaluating Impact of Advance Fuel Cycles

At the end of 2011, a task force of the NEA completed a review of several studies performed in the international community, "to assess the potential impact of P&T [partition and transmutation] on different types of repositories in various licensing and regulatory environments" with the goal to help shape decisions on research and development needs for future alternative fuel cycles [2]. From the US, two studies on the impact on the Yucca Mountain repository footprint from the reduction of radionuclides causing significant heat decay were included [19; 20]. Also, the implication of performance assessment results included in the license application for the Yucca Mountain repository were evaluated [15; 21]. Finally, conclusions from the options study had been reported [4; 5].

Criteria examined included peak dose[8] from undisturbed evolution of the geologic disposal system (undisturbed scenario), decay heat, waste form and volume/mass, uncertainty, and radiotoxicity (which is a concept mostly related to the dose from the inventory for a human intrusion scenario). NEA noted for the peak dose [2, p. 53-57] (Table 1-1):

> For clay and granite in the normal evolution scenarios, $^{129}$I obviously dominates the peak dose if it is disposed of into the repository, either using direct disposal or the reprocessing case. When most of the $^{129}$I is removed from HLW in the reprocessing case, the peak dose is dominated by $^{79}$Se, $^{36}$Cl, and $^{135}$Cs. The effect of MA [minor actinide] transmutation on the peak dose rate is therefore limited for these types of host rock. In the case of the Yucca Mountain…modest impact from actinide P&T…In the case of salt domes, no release of radionuclides is expected in normal evolution.
>
> On the other hand, MA plays an important role in the human intrusion scenarios, expecially in later years (after 1000 years of disposal). MA transmutation will reduce the dose to an intruder by two orders of magnitude. It is therefore reasonable to regard the MA transmutation as a measure to reduce the future uncertainty owing to some unlikely disturbances of all the barriers of the repository system…

In relation to repository foot print, waste form, volume, and mass, NEA noted [2, p. 57]:

> In general, reduction of gallery length by factor of 3-6 can be foreseen by the TRU transmutation in comparison with direct disposal. Additional gain can be also foreseen by separating Cs and Sr, and by storing them for 100-300 years…If very compact configuration is targeted, i.e., a reduction of the repository area by a factor of 100, more than 99% of MA should be removed from the glass waste form…Therefore, P&T can be regarded as an effective measure to design compact repositories or to allow for larger capacity of one repository. It should be noted, however, that such condensed disposal may increase the peak dose rate because of large loading of long-lived FP [fission product].
>
> By introducing fuel recycle, the volume and the mass of HLW can be significantly reduced mainly owing to the recovery of the uranium, while long-lived low- and intermediate-level waste (LILW) would increase…LILW was divided into two categories: short-lived (LILW-SL) and long-lived (LILW-LL). It was found that the volume of LILW-SL (7-20 $m^3$/TWh) is much larger than that of LILW-LL (0.3-3.3 $m^3$/TWh) and HLW (0.1-4.2 $m^3$/TWh). The volume of LILW-SL is dominated by the operation wastes from the power plants, while that of LILW-LL is increased by the operation of reprocessing plants…The

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[8] Not all international programs use probabilistic performance assessments as in the US, which regulates on the mean of the peak dose.

> introduction of P&T of MA seems not be very influential in terms of the total volume of LILW in general.

**Table 1-1. Comparison of peak dose and heat load in salt, clay/shale, granite, and tuff in review of impacts of alternative nuclear cycles with actinide partitioning and transmutation [2].**

| Criterion | Repository | LWR | HLW from reprocessing | HLW from Fast Reactor |
|---|---|---|---|---|
| Dose | Salt Germany | No release | No release | No release |
| (Undisturbed) | Clay/shale France | $10^{-3}$ μSv/TWh-yr ($^{129}$I) | $10^{-4}$ μSv/TWh-yr ($^{129}$I) | $1.5\times10^{-5}$ μSv/TWh-yr ($^{129}$I) |
| | Clay/shale Belgium | $5\times10^{-5}$ μSv/TWh-yr ($^{129}$I) | $10^{-5}$ μSv/TWh-yr ($^{126}$Sn) | $5\times10^{-6}$ μSv/TWh-yr ($^{126}$Sn) |
| | Granite Spain | $10^{-3}$ μSv/TWh-yr ($^{129}$I) | $10^{-5}$ μSv/TWh-yr ($^{135}$Cs) | $2\times10^{-6}$ μSv/TWh-yr ($^{135}$Cs) |
| | Granite Japan | | $<10^{-5}$ μSv/TWh-yr ($^{135}$Cs) | |
| Heat load | Salt | Baseline | Same as baseline | Same as baseline |
| | Clay/shale | | Factor of 3 drift reduction | Factor of 4.2 drift reduction |
| | Granite | | Factor of 3 drift reduction | Factor of 3.5 drift reduction |

In relation to uncertainty, NEA noted in the main text [2, Table 3.6]

> Removal of MA has nearly no effcct on long-term impact under normal evolution of the repository…P&T can minimize estimated resulting doses to population for less probable scenarios: human intrusion, colloid mediated actinide transport, anionic actinide complexes increasing solubility, and oxidizing conditions in the repository environment.

NEA also noted in its conclusions

> The management of uncertainty is an essential feature of the safety case for a geological repository. The role of P&T can be seen as a measure to mitigate the importance of the uncertainty which is inherent to the very long-term nature of the radioactivity. This is achieved essentially by the reduction of the source term.

NEA, in its concluding remarks, expanded on the benefit of advanced fuel cycles that included P&T as follows

> As for uncertainty, P&T can reduce the importance of uncertainties both in normal evolution and in particular those related to hypothetical disruptive scenario that can bring man in direct contact with the disposed waste, since these scenarios seem to be affected by the hazard (radiotoxicity) and not so much by the geology. P&T of the actinides does reduce the hazard of the emplaced materials.

This report explores this broader claim in more detail.

### 1.3.3 2012 Blue Ribbon Commission Evaluation of Impact of Fuel Cycle on Waste Management

In February 2012, the *Blue Ribbon Commission on America's Nuclear Future*, charged to evaluate fuel cycle technologies in terms of "cost, safety, resource utilization and sustainability, and promotion of nuclear non-proliferation and counter-terrorism goals," reported on their findings related to waste management, which are summarized here (Table 1-2). In relation to waste management decisions, the BRC concluded [16, p. 102]:"*In fact, safety, economics, and energy security are likely to be more important drivers of future fuel cycle decisions than waste management concerns per se*."

In their evaluation, BRC [16, p. 102] added an open cycle variation that is mentioned in Table 1-2:

4. Once-through open cycle using high-temperature, gas-cooled reactor (HTGR): In this once-through open fuel cycle, the SNF is in the form of uranium microspheres coated with a tri-structural isotropic (TRISO) layers (a non-structural layer of low density pyrolitic carbon to collect fission products, a layer of high density pyrolitic carbon, a ceramic layer of silicon carbide [SiC], and a final layer of high density pyrolitic carbon). The high density pyrolitic layers protect the silicon carbide layer from thermal, chemical, and mechanical degradation.

The BRC considered a HTGR because of the ability of the high temperatures to be used directly in (a) production of hydrogen by decomposition of water for transportation, (b) desalination of sea water, (c) manufacture of cement and steel, and (d) petroleum refining.

**Table 1-2. Impact on waste management of the once-through, conventional light water reactor fuel cycle with three representative alternative nuclear fuel cycles [16, Table 4]**

| | Once-Through Open (directly dispose UOX) | | Modified Open (reprocess UOX, directly dispose MOX) | Closed Fuel Cycle (reprocess fuel and recycle actinides) |
|---|---|---|---|---|
| Criterion | LWR | HTGR | LWR MOX Modified | Fast Reactor |
| Disposal Safety: Toxicity and longevity | Baseline | Repository: Similar to baseline<br>Fuel Cycle: Similar public and occupational risk from mining and milling | Repository: Reduced TRU wastes. Tailored waste form for ~90% of HLW.<br>Fuel Cycle: 15-20% reduction in public and occupation risk from mining and milling | Repository: Tailored waste form for fission products; potential reduction in dose from TRU if recycle sustained for decades to a couple of centuries<br>Fuel Cycle: ~85% reduction in public and occupational risk from reduced mining and milling;, increased risk from emissions from reprocessing |
| Waste Volume | Baseline | ~10X increase in SNF volume to repository<br>About same LLW non-mill tailings | Similar waste volume: less SNF/HLW but more secondary waste<br>~20% decrease in near-surface wastes, especially mill tailings and depleted uranium. About the same amount of LLW | ~40% increase in waste volume: less HLW but more secondary waste<br>~95% decrease in near-surface wastes, primarily due to reduced mill tailings and depleted uranium<br>~40% decrease in LLW non-mill tailings due to reduced processing at front end of fuel cycle |
| Repository space requirement | Baseline | ~25% reduction due to higher reactor efficiency | Similar to baseline, with some reduction in long-term decay heat generation | ~75% decrease in repository space if TRU waste recovered and recycle is sustained for decades to a couple of centuries |

## 1.4 Report Contents

The remainder of the report first discusses the general aspects of the influence of uncertainty on a disposal system (Chapter 2). The report then discusses the effort necessary to characterize uncertainty and include FEPs in modeling components of the natural barrier system (NBS) (Chapter 3); the non-water form components of the engineered barrier system (EBS) along with a discussion of thermal management (Chapter 4); and the waste form of the EBS (Chapter 5). Appendix A reviews the potential impact of reduced actinide inventory on performance for the disposal system as a whole. Appendix B lists important uncertain parameters for the Yucca Mountain disposal system. Appendix C lists the generic FEPs typically considered by the UFD Campaign. Chapter 5 has a corresponding Appendix D where more detail can be found on waste form degradation.

# 2. INCLUSION OF UNCERTAINTY IN PERFORMANCE EVALUATION

Inclusion of uncertainty is an important aspect of evaluating the performance of a geologic disposal system. It is part of the regulatory definition of a performance assessment of the Environmental Protection Agency (EPA) health standard 40 CFR 197 [6, §197.12; 22]: [9]

> *Performance assessment* means an analysis that: (1) Identifies the features, events, processes, (except human intrusion), and sequences of events and processes (except human intrusion) that might affect the Yucca Mountain disposal system and their probabilities of occurring; (2) Examines the effects of those features, events, processes, and sequences of events and processes upon the performance of the Yucca Mountain disposal system; and (3) Estimates the annual committed effective dose equivalent incurred by the reasonably maximally exposed individual, *including the associated uncertainties*, as a result of releases caused by all significant features, events, processes, and sequences of events and processes, weighted by their probability of occurrence (emphasis added).

This definition identifies four important tasks of a performance assessment (PA): (1) deciding what can happen through identification of FEPs and development of scenarios formed from these FEPs (Item 1 above) that are of regulatory interest, (2) an evaluation of how likely something is to happen through modeling of the probability of the FEPs and scenarios occurring (part of Item 1 above), (3) an evaluation of the hazard of something happening through modeling of the consequences of the FEPs and scenarios occurring (Item 2 above), and (4) an inclusion and evaluation of uncertainties associated with the first 3 tasks (part of Item 3 above).

## 2.1 Types of Uncertainty

### 2.1.1 Identifying What Can Happen

The steps of identifying the universe of what can happen, and then selecting the FEPs and scenarios of regulatory interest can be viewed as (1) identifying the domain of parameters of the probability and consequences models; (2) reducing the domain to that of regulatory interest, and (3) dividing and grouping the domain into scenario regions for probability and consequence modeling (Figure 2-1). For each of these tasks, as suggest in the definition, there is uncertainty.

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[9] The generic health standard, 40 CFR 191, for mined geologic disposal first promulgated by EPA in 1985, and the corresponding implementing regulation, 10 CFR 60, promulgated by NRC, are still in force, and could, in concept be applied to future repositories. However, the evolution in the strategy adopted in site-specific regulations for the proposed Yucca Mountain repository would likely be adopted for a future repository. In particular, NRC has evolved from specifying subsystem requirements on individual components to relying on the PA of the entire system to show which components of the disposal system contribute to safety. Consequently, NRC stated when promulgating 10 CFR 63 that the “generic Part 60 requirements will need updating” [7; 8]. Furthermore, NRC has suggested that regulations for future repositories would likely look similar to 10 CFR 63 in presentations to the BRC and Nuclear Waste Technical Review Board [9; 10]

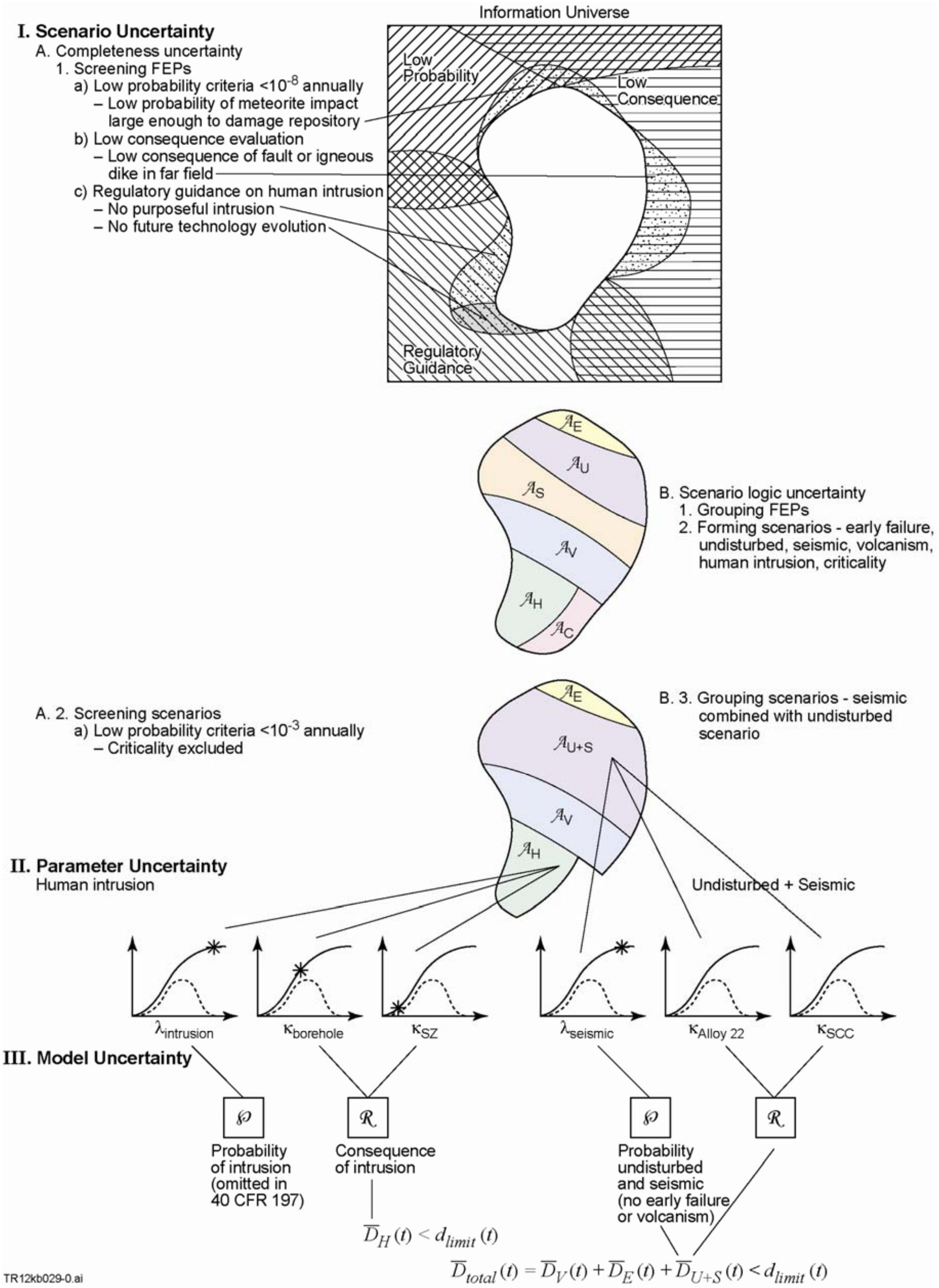

**Figure 2-1. Each of the steps of developing scenarios of regulatory interest and the conceptual translation into mathematical probability and consequence models involve uncertainty.**

### 2.1.2 Three Categories of Uncertainty

Uncertainty in a PA of a geologic disposal system has been typically associated with the three major components: scenarios, models, and parameters [23; 24; 25, §1.3] (Table 2-1):

(1) *Scenario uncertainty*[10] is uncertainty as to (a) whether some unknown behavior exists or some concept has been unknowingly omitted (i.e., whether the FEPs and scenarios formed from these FEPs are comprehensive and complete), and (b) the most appropriate way to group the features, events and processes for modeling (logic).

(2) *Conceptual model uncertainty* is uncertainty about (a) the hypotheses and the appropriate conceptual model forms, and (b) the translation of the conceptual model into a mathematical model, and (c) corresponding adequacy of model verification and validation of the mathematical model. Conceptual model uncertainty applies to both the consequence models and scenario probability models. EPA further commented that [6, p. 61271]

> …"model" uncertainty includes not only whether the processes acting on the site have been correctly represented mathematically and coupled with each other, but also whether the basic understanding of which processes operate, whether there are competing mechanisms that must be considered (e.g., for corrosion or ground-water flow), and the extent to which and conditions under which one mechanism is dominant.

(3) *Parameter uncertainty* is uncertainty in the most appropriate parameter values to use in an applied consequence or scenario probability model. The uncertainty associated with the underlying data is part of parameter uncertainty. EPA further commented that [6, p. 61271]

> …"data" uncertainty can cover broad issues such as whether sufficient data are available, whether the right kind of data are available, whether the data are of sufficient quality, and whether the available data adequately capture what NAS referred to as "the difficulties in spatial interpolation of site characteristics" which "will be present at all times."

Parameter uncertainty can be mitigated through data collection programs and parameter selection guidelines. Parameter uncertainty can be evaluated quantitatively through sensitivity/uncertainty analysis. In a probabilistic approach, parameter uncertainties are described by a probability distribution. In turn, multiple Monte Carlo simulations are often used to propagate individual values of the distribution through the mathematical model of the geologic disposal system to determine the uncertainty (i.e., spread about the mean) of the performance measure, such as the dose to an individual at the accessible environment. The sensitivity analysis can then determine which parameters contribute most to the spread about the mean of the performance measure. Uncertainties in parameters of the natural barrier is often important to explaining the spread in the performance measure, while uncertainty in the inventory amounts is usually not important (Appendix B).

Model uncertainty can be evaluated through alternative conceptual models and their influence quantitatively evaluated by substituting the different conceptual models into the mathematical model of the geologic disposal system to determine the degree to which conceptual uncertainty influences the

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[10] Granted, the terms do not adequately express all the topics included as part of the category. For example, the term "scenario" does not give the impression that it includes the concept of unknowingly omitting some feature, event, or process either in developing the universe of FEPs to consider or in selecting those FEPs to model. The alternative would be to enumerate the numerous sources of uncertainty for a geologic disposal system; however, traditionally these three broad categories have been used in the literature [23]. Furthermore, the NRC refers to these broad categories in its implementing regulation 10 CFR 63.

results In addition, model uncertainty can be qualitatively evaluation through expert judgment and peer review. Verification and validation are important steps to mitigate uncertainty about the correct model form in a PA (Table 2-1).

**Table 2-1. Identification and treatment of uncertainty in performance assessments of geologic disposal systems**

| Identification | | Treatment | | Advanced Fuel Impact |
|---|---|---|---|---|
| Category | Subtype | Mitigate/Reduce | Evaluate/Assess | |
| Scenario | Completeness | 1. Multiple barriers<br>2. Site Selection<br>3. Engineering | 1. Compare to international lists<br>2. Regulator defines approach<br>3. Peer review | 1. Burden to include or exclude FEP (e.g., eases burden to exclude effects of alpha radiation or criticality) |
| | Logic | Use of logic trees or interaction matrices | 1. Peer Review | |
| Parameter | Parameter development | 1. Parameter assignment guidelines (e.g., guidelines on dealing with scale)<br>2. Select bounding parameter value | 1. Sensitivity analysis of varied parameters<br>2. Peer review | 2. Burden to characterize uncertainty (e.g., less burden for solubility since actinides eliminated) |
| | Measurement errors/bias | Data collection quality assurance | | Cannot be known until advanced fuel cycle implemented |
| Model | Conceptual model of FEP | 1. Site characterization/ data collection<br>2. Model validation<br>3. Select bounding model | 1. Sensitivity analysis of conceptual models<br>2. Peer review | 3. Burden to include in model (e.g. same for solubility; decreases burden for colloids) |
| | Mathematical model development | 1. Software quality assurance<br>2. Model verification | | |

Scenario uncertainty captures much of the uncertainty related to scientific questions about a geologic disposal system. The primary means to evaluate the completeness of the FEPs is through the use of international lists of FEPs, expert judgment, and peer review (Appendix C). As suggested by the National Academy of Sciences (NAS) [26], an important means to treat uncertainty related to human behavior and knowledge (i.e., inadvertent human intrusion) is for the regulator to define a stylized calculation about the state of human behavior to avoid evaluating a wide spectrum of speculative futures and technology (Table 2-2) . Important means for the applicant to mitigate scenario uncertainty is through (a) constraints to avoid regions of unknown process behavior, such as thermal constraints for engineered and geologic components; and (b) the careful selection of the repository site to avoid known regions of poorly understood process behavior, such as sites with high quantities of organic matter in aquifers of the natural barrier system which could enhance transport of dissolved radionuclides.[11]

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[11] Although the terms are not used within this report, in the US, uncertainty is typically divided into two classes for propagating uncertainty in a PA calculation: aleatoric and epistemic. Aleatoric uncertainty represents future aspects of the disposal system that have a random character, whose uncertainty is deemed irreducible by further site characterization. The strategy for propagating aleatoric uncertainty is by defining scenarios whose probability of occurrence is expressed with mathematical probability models. Thus, aleatoric uncertainty is closely associated with scenario uncertainty. Epistemic uncertainty represents uncertainty about aspects of the disposal system that are imprecisely known, but, in principle, could be rendered more precise by further observation or experiment. For propagating epistemic uncertainty, the primary strategy is to use alternative conceptual consequence models or use probability density functions to represent uncertainty for parameters of the consequence models. Thus, epistemic uncertainty is closely associated with conceptual model and parameter uncertainty.

**Table 2-2. Examples of treatment of scenario uncertainty in performance assessments**

| | | Treatment | |
|---|---|---|---|
| Category | Subtype | Mitigate/Reduce | Evaluate/Assess |
| Scenario | Completeness<br>1. Features | 1. Site selection to avoid complicated features and likelihood of unknown features (e.g., avoid complex geology) | |
| | 2. Events | 1. Site selection to lower probability (e.g., geology allowing deep disposal and area lacking rare resources to lower probability of human intrusion)<br>2. Engineering to avoid impact of event (e.g., add backfill to mitigate impact of seismic shaking) | Regulator defines approach<br>a. Events not to be considered: purposeful intrusion<br>b. Stylized circumstances for inadvertent intrusion without driller exposure<br>c. Screening criteria: $>10^{-8}$ annually |
| | 3. Processes | 1. Site selection to avoid process (e.g., avoid area with large amount of organics along groundwater pathway)<br>2. Engineering design constraints to avoid areas of poorly known behavior (e.g., add corrosion resistant package to avoid analysis of cladding degradation or thermal constraints on design to maintain backfill integrity) | Regulator defines approach<br>a. Processes not to be considered: criticality after $10^4$ yr<br>b. Specify bounding conditions: bound water consumption in biosphere at 2L/d<br>c. Screening criteria: process does not influence timing or magnitude of dose |

### 2.1.3 Use of Multiple Barriers to Mitigate Uncertainty

Multiple barriers in a geologic disposal system are a means of mitigating the uncertainty about whether FEPs (and scenarios formed from these FEPs) are comprehensive and have been adequately considered (i.e., scenario uncertainty). By 1976, a general consensus had developed about the desirability of multiple barriers for providing waste isolation in repositories [27]. Multiple barriers expanded the range of geologic media of interest because engineered barriers of the disposal system could complement less favorable geologic characteristics while exploiting other advantageous geologic characteristics, including lack of hydrocarbons in close proximity. For example, Sweden incorporated the multiple barrier concept into their design for a granite repository for SNF by using a clay backfill and highly corrosion resistant package of titanium (KBS I) or copper (KBS III) [28, p. 295]. Also, the Interagency Review Group (IRG) for Nuclear Waste Management, formed by President Carter in 1979 concluded that multiple barriers (specifically, the waste form and especially, the package) were a means of compensating for geologic uncertainty [29; 30, App. A; 31, p. 3-3]. Yet, the Nuclear Regulatory Commission (NRC) noted that engineered barriers also had uncertainty [7, §63.102(h)]:

> Although the composition and configuration of engineered structures (barriers) can be defined with a degree of precision not possible for natural barriers, it is recognized that except for a few archaeologic and natural analogs, there is limited experience base for the performance of complex, engineered structures over periods longer than a few hundred years, considering the uncertainty in characterizing and modeling individual barriers. These uncertainties are addressed by requiring the use of a multiple barrier approach;…

NRC emphasized that multiple barriers were to compensate for residual scenario uncertainty in the preamble for the Yucca Mountain regulations in 2001 [7, p. 55747]:

> Part 63 not only requires DOE to account for uncertainty in its performance assessment but also contains a number of other requirements (e.g., use of multiple barriers, performance confirmation program) to compensate for residual uncertainties in estimating performance. The Commission will consider all these requirements in determining whether it has sufficient confidence (i.e., reasonable expectation) that DOE has demonstrated or has not demonstrated the safety of the repository.

## 2.2 Measure of Uncertainty Not Set by US Regulations

EPA requires the inclusion of all uncertainty to provide as unbiased an estimate as practicable of the "mean value of the distribution of calculated doses." Uncertainty is tied to the standard of proof of reasonable expectation where EPA described characteristics of reasonable expectation (§197.14) as follows

> Characteristics of reasonable expectation include that it: (a) Requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long-term performance; (b) Accounts for the inherently greater uncertainties in making long-term projections of the performance of the Yucca Mountain disposal system; (c) Does not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence; and (d) focuses performance assessment and analyses upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values.

Neither EPA nor NRC establishes an indicator and a corresponding measure for uncertainty in a PA in the current regulations (e.g., a numerical limit on the "maximum" uncertainty permitted on the spread in the dose results).[12] In fact, in a response to comments suggesting that NRC specify an acceptable level of uncertainty, NRC replied in the preamble [7, p. 55748]:

> The approach defined in part 63, which requires DOE to fully address uncertainties in its performance assessment rather than requiring DOE to meet a specific level of uncertainty, is appropriate. The treatment of uncertainty in DOE's performance assessment will be an important part of NRC's review…Although the Commission does not require an "accurate" prediction of the future, uncertainty in performance estimates cannot be so large that the Commission cannot find a reasonable expectation that the postclosure performance objectives will be met.

Consequently, there is no penalty for uncertainty; instead, it must be fully addressed and displayed such that NRC has a reasonable expectation that the licensee has "demonstrated the safety of the repository."[13]This is a reasonable approach because a measure of acceptable uncertainty would likely need to be tied to the value of the dose in relation to the limit (i.e., large uncertainty about a mean dose value that is far below the dose limit would likely engender less regulatory concern than small uncertainty about a mean value that is only slightly below the dose limit).

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[12] The EPA generic health standard defined a limiting complementary cumulative distribution function (CCDF), defined by two points, for comparison with the calculated CCDF of cumulative releases. The limiting CCDF defines the shape of the distribution of cumulative releases and, in a sense, the uncertainty permissible when very near the limit. However, this is not truly a limit on uncertainty, because a great variety of distributions some with and some without much uncertainty could be less than the limiting CCDF.

[13] Although the NRC regulation defines neither an uncertainty measure nor a limit, the Yucca Mountain Project (YMP) Review Plan does ask for a display of the 5% and 95% percentiles of the expected peak dose in addition to a display of the whole distribution of uncertainty. The spread between the 5% and 95% percentiles normalized by the mean, similar to the coefficient of variation (variance normalized by the mean), could be used as a measure of uncertainty, but these measures change with time and so an average or maximum would have to be chosen.

For example, a reduction in the overall inventory disposed in a repository would not materially reduce the overall uncertainty associated with a disposal system, even though it would reduce the dose (provided one kept the waste type, the thermal loads for the repository/package the same and the geologic variation and fluid flow uncertainty remained the same for the smaller repository[14]). This concept, which is akin to changing the value of a fixed parameter, can be illustrated notionally by plotting the probability density function (PDF) of the peak doses, whenever they occur over the regulatory period (~$10^6$ yr for proposed Yucca Mountain repository), with dose as the $x$-axis (e.g., mSv/yr) (Figure 2-2, Curves A and B). The mean of the PDF is the expected (mean) value of these peak doses, regardless of time (i.e., $\mathcal{E}\{{}^{\max}D_{total}\}$ ).[15] Any uncertainty from scenarios, models, or parameters associated with geologic disposal may be of less regulatory concern if the corresponding reduction in dose is far below the limit (Figure 2-2, Curve B).

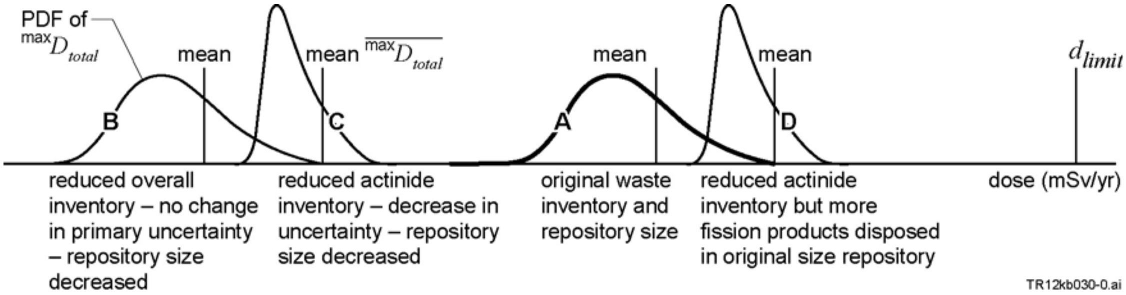

**Figure 2-2. Possible changes in mean peak dose and uncertainty of the peak dose for a geologic disposal system when the radionuclide content of the disposed waste is changed. For Curves B, C, and D, the thermal loads and thermal constraints are assumed to be similar. Also, the geologic variation and fluid flow in the natural barrier are assumed to be similar.**

For an advanced fuel cycle, the situation might or might not be similar to reducing the inventory. If an actinide radionuclide is a dominant contributor to dose, then the position of the mean dose would decrease similar to a reduction in overall inventory, possibly to a point that there is less regulatory concern. In addition, if a characteristic of an actinide is also important in causing the spread in dose results (e.g., uncertainty in retardation of the actinide), then its reduction would also reduce overall uncertainty (Figure 2-2, Curve C).

If an actinide radionuclide is not a dominant contributor to dose, then the position of the mean dose would not change. Although a less common occurrence, in concept, some characteristic of an actinide radionuclide could still be important to causing the spread in the dose results about the mean without being a dominant contributor. For this situation, the uncertainty and, thereby, the spread about the mean

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[14] Because of the change in repository size, the uncertainty might not be the same in a highly heterogeneous geologic environment, but large heterogeneity is usually avoided in site selection. Furthermore, we are speaking of less than a factor of 10 decrease or factor of 2 increase in size. In the limit, as the repository size decreased to the size of one package, most spatial variability in an important parameter such as fluid flow at the package, for example, would disappear leaving only the spatial variability of corrosion rates on the one package. However, the underlying uncertainty in what value to use for fluid flow, for example, would still remain.

[15] US regulations actually measure the mean of the dose over time, where the maximum of this measure must be less than the limit (i.e., ${}^{\max}\bar{D}_{total}(t) < d_{limit}$). The use of the PDF of peaks more readily shows the influence of uncertainty over the entire spectrum of behavior, provided the uncertainty as to when the peak dose occurs during the regulatory period is of secondary importance. A plot of a PDF of $D_{total}(t)$ when the mean is at its maximum would show only the contribution of uncertainty from a particular set of components at a particular time (i.e., uncertainty varies with time as various components of the disposal system influence the dose; hence, the uncertainty shown by the PDF of $D_{total}(t)$ at its maximum could change with only a shift in when the peak occurred, which would complicate the comparison).

would decrease, but the decrease would be less, and usually much less, than if the actinide was an important contributor to dose. On the other hand, it is also conceivable, in concept, that the removal of important contributing actinides could actually increase uncertainty if uncertainty associated with the remaining fission products was greater than the uncertainty associated with the removed actinides.

## 2.3 Treatment of Uncertainty Related to Inadvertent Human Intrusion

Although a measure of uncertainty is not defined, NRC does discuss the expected treatment of uncertainty for inadvertent human intrusion as follows.

### 2.3.1 Regulatory Basis in US

Anthropogenic events could potentially influence disposal system performance through deliberate and inadvertent human intrusion, and by human influences on the climate. In the US, EPA and NRC have adopted a strategy of narrowing the focus of speculative anthropogenic disruption to that of inadvertent human intrusion. Furthermore, the treatment of uncertainty related to the disruptive inadvertent human intrusion scenario class has used the strategy of using a stylized calculation that defines the state of human behavior (i.e., current technology and environmental conditions) to avoid evaluating a wide spectrum of speculative futures caused by technology and human induced climate change (Table 2-2).

However, the treatment in the US has evolved from the strategy first promulgated in the 1985 generic health standard, 40 CFR 91, in which releases from inadvertent human intrusion were included in the general PA, conditioned by its probability using constraints on type (i.e., exploratory drilling) and frequency of drilling intrusion. Currently, the inadvertent human intrusion event is not included in the probabilistic dose calculations for Yucca Mountain in the EPA health standard, 40 CFR 197, or the NRC implementing regulation, 10 CFR 63, consistent with a recommendation by NAS after reviewing the disposal regulations as requested by Congress [26; 32].

Furthermore, NAS noted, and NRC concurred, that exposure to those inadvertently drilling into a repository and subsequent dispersal of drilling material is not based on characteristics of the designed disposal system, but rather the waste inventory. Specifically NRC stated [7, p. 55761]

> NAS concluded, and the Commission agrees, that analysis of the risk to the public or the intruders (i.e., drilling crew) from radioactive drill cuttings left unattended at the surface for subsequent dispersal into the biosphere would not fulfill the purpose of the human intrusion calculation because it would not show how well a particular repository site and design would protect the public at large. Rather, an analysis of the hazard of particulate HLW left on the surface would be dominated by assumptions subject to significant speculation and uncertainty regardless of the particular site or design under evaluation. Additionally, the release to the surface represents a one-time release with no long-term effect on repository barriers

Thus, dose to a driller is not thought pertinent and evaluated in the most current US regulations for nuclear waste disposal. In turn, a reduction in the actinide inventory to reduce the dose to a driller would not be pertinent.

However, NRC further noted that some evaluation of groundwater releases via the pathway created by the inadvertent human intrusion was warranted:

> Alternatively, releases to the ground-water pathway can be adversely influenced over a long period of time by an intrusion event that affects barriers of the repository (see the discussion on barriers). Therefore, an appropriate test of the resilience of the repository is an evaluation of the effects of intrusion on releases in the ground-water pathway.

In the current health standard 40 CFR 197 for the proposed Yucca Mountain repository, EPA defined a stylized calculation for inadvertent human intrusion where the calculated dose (unconditioned by the probability of the event) is compared to a limit of 0.15 mSv/yr in the first $10^4$ yr and 1 mSv/yr thereafter. In the stylized calculation, an inadvertent human intrusion results is the creation of a fast path from the repository to an aquifer (that bypasses the unsaturated zone portion of the natural barrier at Yucca Mountain), but retains the remainder of the natural barrier in the aquifer to the accessible environment at least 5 km away (~18 km away for the inhabitants at Yucca Mountain), where transport of radionuclides, and particularly actinides, are reduced. EPA specifies use of the current state of human behavior (e.g., current technology), under the fairly reasonable assumption that the waste is most dangerous to humans with our current state of knowledge and technical capability [33]. To elaborate, the circumstances of human intrusion are

> (a) There is a single human intrusion as a result of exploratory drilling for ground water; (b) The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository; (c) The drillers use the common techniques and practices that are currently employed in exploratory drilling for ground water in the region surrounding Yucca Mountain; (d) Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole; (e) Only releases of radionuclides that occur as a result of the intrusion and that are transported through the resulting borehole to the saturated zone are projected; and (f) No releases are included which are caused by unlikely natural processes and events.

### 2.3.2 Doses from Human Intrusion Disturbance

Although numerous international studies have evaluated the influence of advanced fuel cycles on system performance for undisturbed conditions, the circumstances of human intrusion vary in the international community and so the implications of human intrusion vary. Hence, results specific to the US circumstance are necessary. The UFD Campaign is developing the capability to model different disposal environments and waste form options. Although under development, the demonstration results from the generic configurations of crystalline and salt repositories (using material properties from real sites), give a rough indication of behavior (Appendix A). For a generic repository in crystalline rock with properties similar to the proposed Swedish repository, the doses at a 5-km boundary are 5 orders of magnitude below the 0.15 mSv/yr limit in the first $10^4$ yr for intrusion into a package containing 10 assemblies of commercial SNF from a pressurized light water reactor (PWR). Not only are doses far below the limit, but mean annual dose is from the $^{129}$I fission product, which surpasses $^{241}$Am, $^{243}$Am, $^{239}$Pu and $^{240}$Pu actinides after only a few thousand years.

For a generic repository in salt, with features similar to those of the Waste Isolation Pilot Plant (WIPP) in southern New Mexico, the mean peak doses at a 5-km boundary are 3.5 orders of magnitude below the 0.15 mSv/yr limit in the first $10^4$ yr and 3 orders of magnitude below the 1 mSv/yr limit after $10^4$ yr from intrusion into a package containing 10 assemblies of commercial PWR SNF. Although the actinides $^{237}$Np and $^{239}$Pu are the dominant contributors to the mean peak dose for the repository in salt, the doses for both the salt and crystalline rock repositories are so far below the limit that any reduction in dose or uncertainty would not bring about a measureable benefit (Appendix A).

## 2.4 General Treatment of Uncertainty

The evaluation of what can happen to the disposal system consists of determining (1) a scenario class of all the processes considered part of undisturbed evolution of the disposal system, and (2) scenario classes of external agents acting upon the disposal system along with pertinent processes. As listed in the FEPs tables (Appendix C), the agents include geologic events, atmospheric climate events, anthropogenic events, and planetary events. Although US regulations have described the strategy to use for dealing with the scenario uncertainty associated with the anthropogenic events, the strategy for dealing with uncertainty from other external agents is less specific, and for the undisturbed scenario class, quite general.

### 2.4.1 Climatic, Geologic, and Planetary Disturbances to the Disposal System

The general categories of external agents acting upon the disposal system (besides an anthropogenic agent) are climatic, geologic, and planetary (Appendix C). Planetary events include meteorite impact, changes in earth's magnetic field, and solar flares. For this type of external agent, a change in inventory will have no primary influence on the uncertainty of the event itself and so spread of the results about the mean will not be influenced.

Climatic changes include natural variations in precipitation and temperature as well as glacial effects. Similar to planetary events, a change in inventory will have no primary influence on the uncertainty of the event itself. There may, however, be a secondary effect in that more oxygenated water may reach to the depths of the repository, if percolation increases substantially. Even then, the presence of oxygenated water is not by itself enough to produce oxic conditions within the repository if a reducing agent (such as iron is present). The oxic conditions at Yucca Mountain, provide an upper bound on behavior (Appendix A). Based on the results at Yucca Mountain, significant climatic change, which causes substantially increased percolation, would have to occur in concert with a fairly dramatic disruption of the EBS (such as the disruption caused by an igneous event) for actinides to become important.

Geologic agents include (1) long-term processes such as dissolution and tectonic activity causing uplift and folding, (2) igneous activity, and (3) seismic activity. Here again, a change in inventory will have no primary influence on the uncertainty of the event. There may, however, be a secondary effect in that a change in the configuration of the disposal system may make other radionuclides such as actinides more important.

Natural disturbances may disrupt the engineered barrier system. In other instances, natural disturbances may also create fast paths to the accessible environment that bypass and some of the features of the natural barrier. Somewhat similar to the uncertainty associated for anthropogenic events, EPA and NRC adopted the strategy to define the uncertainty of natural disturbances of regulatory interest, which focused on disruption of the EBS. EPA and NRC did not identify fast paths that bypassed features of the natural barrier of regulatory interest (instead, fast paths were investigated for inadvertent human intrusion). For the proposed Yucca Mountain repository, EPA stated [6, §197.36]

> (c) For performance assessments conducted to show compliance with §§ 197.20(a)(2) and 197.25(b)(2), DOE's performance assessments shall project the continued effects of the features, events, and processes included in paragraph (a) of this section beyond the 10,000-year post-disposal period through the period of geologic stability. The DOE must evaluate all of the features, events, or processes included in paragraph (a) of this section, and also:
>
> (1) The DOE must assess the effects of seismic and igneous scenarios…
>
>> (i) The seismic analysis may be limited to the effects caused by damage to the drifts in the repository, failure of the waste packages, and changes in the elevation of the water table under Yucca Mountain. NRC may determine the magnitude of the water table rise and its significance on the results of the performance assessment, or NRC may require DOE to demonstrate the magnitude of the water table rise and its significance in the license application…
>>
>> (ii) The igneous analysis may be limited to the effects of a volcanic event directly intersecting the repository. The igneous event may be limited to that causing damage to the waste packages directly, causing releases of radionuclides to the biosphere, atmosphere, or ground water.

> (2) The DOE must assess the effects of climate change. The climate change analysis may be limited to the effects of increased water flow through the repository as a result of climate change, and the resulting transport and release of radionuclides to the accessible environment. The nature and degree of climate change may be represented by constant climate conditions. The analysis may commence at 10,000 years after disposal and shall extend through the period of geologic stability. The NRC shall specify in regulation the values to be used to represent climate change, such as temperature, precipitation, or infiltration rate of water.
>
> (3) The DOE must assess the effects of general corrosion on engineered barriers. The DOE may use a constant representative corrosion rate throughout the period of geologic stability or a distribution of corrosion rates correlated to other repository parameters.

Geologic agents, such as seismic and igneous activity, are site-specific. Initially, the frequency and severity would be addressed during site selection and later during site characterization. Because EPA and NRC did not identify fast paths through the natural barrier, natural disturbances have the same the characteristics in the natural barrier as for the undisturbed scenario. Only more extensive damage to the EBS is of interest.[16] The change in EBS configuration, may make other radionuclides such as actinides more important, in which case, a reduction in actinide inventory would reduce the dose. However, the overall uncertainty would not likely change except in the manner already described for the undisturbed scenario, because parameters of the natural barrier have such an important influence on the uncertainty in the dose (Appendix B).

Because a generic evaluation cannot get into specifics as to the frequency and severity of a natural disturbance for determining the change in the EBS configuration and because of the rough similarity with the undisturbed evolution for the natural barrier, natural disturbances are not discussed further in this report except for the results reported for the proposed Yucca Mountain repository. Actinides were not important contributors to dose except for igneous disruption in which all the waste packages were assumed destroyed (Appendix A).

In the course of PA iterations for the proposed Yucca Mountain disposal system, the relative importance scenarios to determining dose changed. Although doses were initially dominated by the undisturbed scenario, the dose was eventually dominated by natural disturbances, as site characterization and the EBS design progressed. Provided understanding of the disposal system has progressed such that the expected doses are far below the regulatory limit (Figure 2-2, Curve B), the fact that dose may be dominated by a natural disturbance is immaterial.

### 2.4.2 Doses from Undisturbed Scenario of the Disposal System

As has been demonstrated by several studies [1; 2] and recent demonstration calculations by UFD [12] (Appendix A), the hypothetical total doses calculated for the evolution of the repository in the undisturbed scenario are dominated by doses from mobile fission products such as technetium and iodine ($^{99}$Tc and $^{129}$I) for geologic disposal systems in anoxic environments (crystalline rock and clay/shale environments) and with usually no release from salt environments. Actinides such as neptunium and plutonium ($^{237}$Np, $^{239}$Pu, and $^{240}$Pu) may contribute but they are not the dominant source for the total dose. As noted in the next chapter, this result is due to the anoxic geochemical conditions of the natural barrier system.

For UFD demonstration calculations for a 140,000-MTHM repository for commercial SNF, mean peak dose was $10^{-5}$ mSv/yr for mined geologic disposal and $10^{-10}$ mSv/yr for borehole geologic disposal, both

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[16] However, the volcanic eruptive scenario subclass of igneous intrusion is quite different in that only several packages are disturbed and the pathway is atmospheric. For this subclass, actinides are a dominant contributor to calculated expected dose, but doses are far below the regulatory limit for the proposed Yucca Mountain repository [15, Fig. 8.2-10].

in crystalline rock. These doses are far below the limits set for the proposed Yucca Mountain repository (0.15 mSv/yr in the first $10^4$ yr or 1 mSv/yr thereafter). Hence, similar to performance after human intrusion, any reduction in dose or uncertainty would not bring about a measureable benefit.

The goal of the waste management system is safe disposal as defined by the consensus expressed in regulations. The goal is not to endlessly seek to reduce doses, which could be accomplished by developing numerous small repositories. Hence, the waste management system may respond to a reduction in actinide inventory and corresponding heat load by disposing more waste in the same repository area and/or in larger capacity waste packages, if allowed by future social/political agreements for siting a repository. In this case, the mean peak doses might not decrease, because of the increase amount of fission products (Figure 2-2, Curve D). For this situation, further evaluation of the uncertainty associated with advanced fuel cycles is warranted.

### 2.4.3 Uncertainty Associated with the Undisturbed Scenario

NRC, in its implementing regulation 10 CFR 63, provided general guidance for the treatment of uncertainty by requiring inclusion of parameter uncertainty, consideration of model uncertainty, and the technical basis for inclusion or exclusion of specific FEPs as part of a PA (Table 2-1); specifically [14, §63.114],

> Any performance assessment used to demonstrate compliance with § 63.113 must: (a) Include data related to the geology, hydrology, and geochemistry (including disruptive processes and events) of the Yucca Mountain site, and the surrounding region to the extent necessary, and information on the design of the engineered barrier system used to define parameters and conceptual models used in the assessment. (b) *Account for uncertainties and variabilities in parameter values* and provide for the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment. (c) *Consider alternative conceptual models of features and processes* that are consistent with available data and current scientific understanding and evaluate the effects that alternative conceptual models have on the performance of the geologic repository. (d) Consider only events that have at least one chance in 10,000 of occurring over 10,000 years. (e) *Provide the technical basis for either inclusion or exclusion of specific features, events, and processes* in the performance assessment. Specific features, events, and processes must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, would be significantly changed by their omission… (emphasis added).

As noted in Chapter 1, FEPs are the starting point for evaluating dose and, thus, a convenient point to qualitatively evaluate the impact of advanced fuel cycles on the undisturbed evolution of the disposal system. Three aspects of the impact are pertinent here (Table 2-1): (1) the impact on the technical basis to include or exclude a FEP in models of the disposal system for the analysis; (2) the effort to include the FEP in the modeling system; and (3) the effort to characterize the parameter uncertainty related to a FEP if included in the analysis.

To elaborate, for any changes caused by advanced fuel cycles to systems of the geologic disposal, the project will need to carefully characterize uncertainty associated with the undisturbed scenario. For example, in the case of a new waste form such as HLW disposed in an electro-chemical ceramic, the project will need to (1) "provide the technical basis for either inclusion or exclusion of features, events, and processes" on various modes of failure and degradation. (2) "consider alternative conceptual models" that equally explain modes of degradation, and (3) "account for uncertainties and variabilities in parameters values" for the mathematical models developed for the PA. Conducting these tasks is a large part of the effort in conducting a PA for the evaluation of the undisturbed evolution of the geologic disposal system. Chapters 3, 4, and 5 discuss these three aspects for FEPs associated with the undisturbed evolution of the repository.

# 3. UNCERTAINTY IN NATURAL BARRIER AND INFLUENCE OF FUEL CYCLE

## 3.1 Approach

In Chapter 3, we summarize the impact of different radionuclide inventories from advanced nuclear fuel cycles on the natural barrier with a focus on geochemistry in the context of the current state of knowledge and the reasonable expectations of future advances likely to be made in the field. In their review, NEA noted [2, Table 3.6] "…P&T can minimize estimated resulting doses to population for less probable scenarios: human intrusion, colloid mediated actinide transport, anionic actinide complexes increasing solubility, and oxidizing conditions in the repository environment." The latter three points are discussed here.

FEPs are the starting point for evaluating dose and, thus, a convenient point to qualitatively evaluate the impact of advanced fuel cycles on the undisturbed evolution of the disposal system. FEPs allow a screening of characteristic properties of each component of a repository to be evaluated.[17] Numerous FEPs are associated with the natural barrier (Table 3-1).

## 3.2 Evaluation of Features, Events, and Processes of Natural Barrier

A significant number of FEPs relate to the properties, behavior and performance of the natural system with respect to its ability to retard or dilute the quantities of radionuclides that reach the accessible environment, For the purpose of evaluating the possible incremental decrease in uncertainty caused by removing actinides, these FEPs can be aggregated into seven sets of similar topics based on the processes impacting or impacted by the conditions of the host rock and accompanying pathways to the accessible environment:

1. Stratigraphic, mechanical, and hydrologic properties of the host rock and natural system
2. Hydrologic processes of flow through the host rock and natural system
3. Geochemical conditions in the host rock and natural system, and their effect on (a) radionuclide solubility and speciation, (b) complexation with carbonates and organics, (c) sorption, and (d) colloid-facilitated transport.
4. Biological processes
5. Thermal processes
6. Gas sources
7. Nuclear criticality

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[17] The UFD Campaign developed a research and development (R&D) roadmap for use as an evaluation and prioritization tool for R&D opportunities that could be pursued by the campaign [34]. Using a similar approach, the roadmap is organized according to FEPs that pertain to a variety of geologic disposal scenarios.

**Table 3-1. Features, events, and process related to the natural barrier system are similar for both the open and closed fuel cycles except for geochemical processes (Appendix C).**

| | | Nuclear Fuel Cycle Option | |
|---|---|---|---|
| UFD FEP | FEP Category | Open | Closed |
| 2.2.01 | Evolution of excavation disturbed zone (EDZ) | Include | Include |
| 2.2.02 | Stratigraphy and properties of host rock | Include | Include |
| 2.203 | Stratigraphy and properties of other geologic units | Include | Include |
| 2.2.05 | Flow and Transport pathway properties (e.g., via fractures, faults and their evolution over time) | Include | Include |
| 2.2.07 | Mechanical process on geologic units (e.g., subsidence, salt and clay deformation, drift collapse | Include | Include |
| 2.2.08 | Hydrologic processes (flow through the natural system) | Include | Include |
| 2.2.09 | Geochemical processes: | | |
| | chemical characteristics of groundwater | Include | Include |
| | Chemical interactions and evolution of groundwater | Include prior to repository; Exclude after repository | Include prior to repository; Exclude after repository |
| | Radionuclide speciation and solubility | Exclude (i.e., no change from EBS) | Exclude (i.e., no change from EBS) |
| 2.2.10 | Chemical transport processes | | |
| | Advection and Diffusion of dissolved radionuclides | Include actinides and Fission products | Include fission products |
| | Sorption of dissolved species | Include actinides and Fission products | Include fission products |
| | Sorption/filtration/stability of colloids | Include as retardation factor for actinides | Exclude for fission products |
| | Complexation with organics | Exclude | Exclude |
| | Complexation with carbonates | Exclude (i.e., no change from EBS carbonates species of actinides) | Exclude |
| | Dilution of radionuclides with groundwater | Include | Include |
| | Colloid-facilitated transport | Include for actinides | Exclude |
| | Dilution of radionuclides with stable isotopes | Include for $^{129}$I for salt repository; dependent on brine content of pathways for other repository environments | Include for $^{129}$I for salt repository; dependent on brine content of pathways for other repository environments |
| 2.2.10 | Biological processes | Exclude | Exclude |
| 2.2.11 | Thermal processes (e.g., convection, buoyancy, thermal diffusion, thermal alteration of geologic units | Exclude through thermal constraints | Exclude through thermal constraints |
| 2.2.12 | Gas sources and effects | Include in salt and clay repository environments | Include in salt and clay repository environments |
| 2.2.14 | Nuclear criticality in far field | Exclude | Exclude |
| 2.2.16 | Undetected features | Exclude | Exclude |

While each of these sets of FEPs is critical to the characterization of the natural system as a barrier to radionuclide migration, only the third set, geochemical conditions, is relevant for the natural barrier for the more limited objective of this study—assessing the impact of advanced fuel cycles on uncertainties. The reason for this large reduction in pertinent FEPs is that the principal difference among the fuel cycle alternatives, as it relates to geologic disposal, is the inventory of radionuclides produced. The radionuclide differences lead to different conditions for transport through the host rock and natural system. Thermal effects are important at the interface with the EBS but for the purposes of the discussion in this report we have included most of the thermally perturbed portion of the host rock with the EBS (e.g., 100 m around a disposal borehole). Otherwise, there is a tedious repetition of factors related to both the natural barrier and EBS.

Because our focus is on the uncertainty in the safety case for different fuel cycles, only a limited analysis is required to capture the key determining factors. In essence, the question with respect to the performance of the natural system reduces to the following question: do the differences in inventory afforded by a closed fuel cycle impact the uncertainty in the models for radionuclide migration to the accessible environment? To answer this question, we first recognize that the ultimate need for a geologic repository is independent of fuel cycle. Even if isotopes of plutonium and minor actinides are reduced to a very low level in the disposed materials, the fission products will be present in quantities that basically are proportional to the energy generated via the nuclear fission reactions. Some of these fission product radionuclides are long lived, including $^{99}$Tc (half-life of $2.14 \times 10^5$ yr) and $^{129}$I (half-life of $1.57 \times 10^7$ yr), which require long-term isolation from the environment. Thus, for long-term isolation by the geology of the host rock and natural system, fission products are present for all fuel cycles, and the issue reduces to the incremental increase in uncertainty associated with demonstrating that plutonium, uranium, and minor actinides will be isolated from the accessible environment.

## 3.3 Chemical Conditions of the Host Rock and Natural Barrier System

It is instructive to examine the existing PA studies performed for the US and international repository programs [2]. A general feature of these PAs is the role that geochemistry of the host rock and far-field groundwater plays in controlling the results. The solubility of most actinides is a strong function of pH and redox conditions of the groundwater flow. Under reducing conditions and neutral or basic pH conditions, actinides are very insoluble, which leads to an extremely small source term for radionuclide releases. These conditions are commonly expected in all repository host rocks located below the water table. Most granite and clay repository disposal concepts fall into this category, including deep boreholes in crystalline basement rock. Disruptive scenarios that involve the entry of oxidizing fluids into the repository are possible, but generally speaking, the probability of these scenarios can be minimized through proper site selection. Salt is something of a special case, in that, for a properly sited salt repository, the limited quantity of water in the vicinity of the waste will minimize releases, independent of the geochemical conditions. Nevertheless, the fluid geochemistry in a salt repository is also expected to be reducing, leading to low solubility for scenarios involving the entry of fluids into the repository. Similar geochemical arguments regarding redox conditions apply to actinide sorption, in that reducing conditions lead to very large sorption coefficients, and hence immobility (with the caveat that the sorption sites are themselves immobile rather than colloidal as discussed in Section 3.4).

Because of these arguments, releases from repositories are generally driven by the more mobile fission products such as $^{99}$Tc and $^{129}$I, rather than by the actinides as noted in the previous chapter. It follows that as long as these models capture the key reactive transport processes of the actual system, then the uncertainties will not be reduced by eliminating or minimizing the presence of actinides in the repository: the dose at the receptor site is typically controlled by the presence of fission products that are present in the repository under all fuel cycles.

In addition, under certain geochemical conditions, actinides such as neptunium can form anionic complexes that limit their propensity to sorb to rock surfaces. This situation is more likely in groundwater systems that have significant organic material present, or in the near-field in repositories containing organic material that is subjected to microbial degradation. Also, a release pathway that involves transport of the radionuclides to a carbonate-rich groundwater, removal of actinides via partitioning and transmutation will likely reduce the uncertainty in performance for these cases. However, an alternative is to select sites and use repository designs that limit the amount of organic material present. Furthermore, in disposal systems in which reducing conditions are maintained, the degree of formation of carbonate complexes should be minor.

In this context, the Yucca Mountain disposal system is a special case in the sense that it was located above the water table in an oxidizing environment. Even for this case, however, for most scenarios of repository evolution, the actinides comprised only a small incremental contribution to the total dose to the receptor, which was more typically dominated by the mobile fission products (Appendix A). Exceptions to this general result are colloid-facilitated transport of plutonium, and dissolved transport of neptunium $^{237}$Np, an actinide that is relatively soluble in the +5 valence state. Transport of both of these species was studied extensively for Yucca Mountain disposal system [13; 35]. The uncertainty for $^{237}$Np solubility was relatively well constrained and less important than the uncertainty associated with uranium solubility in explaining the variability in the results (Appendix B). The uncertainty of the colloid concentration in the groundwater associated with colloid-facilitated transport mechanisms was an important parameter, but less so than the uncertainty for parameters related to package degradation, fluid flux in the saturated zone, and uranium solubility (Appendix B). Hence, removing this uncertainty would not substantially remove the spread in the dose.

## 3.4 Uncertainty Associated with Colloidal Transport

Conceivably, one conceptual model uncertainty that may be impacted by the quantities of actinides placed in a repository is the nature of potential colloid-facilitated transport. In some chemical environments, actinides are somewhat susceptible to accelerated transport (compared to aqueous transport of a sorbing species) by the mechanism of incorporation into mobile colloid particles via precipitation or sorption mechanisms (e.g. [36]). Since actinides are generally highly sorbing and sparingly soluble under most conditions anticipated in a repository system, colloid-facilitated transport could lead to farther, faster migration of actinides than would otherwise be expected for such species. It follows that a partitioning and transmutation fuel cycle that reduces the quantities of actinides in the repository would, as a by-product of these operations, lead to reduced uncertainties in processes associated with this transport mechanism.

However, several factors argue against conceptual uncertainty in colloid-facilitated transport being an important consideration in judging whether the choice of fuel cycle matters to overall uncertainty. First and foremost, we observe that despite the uncertainty in the basic transport mechanism, most PAs of repositories yield doses controlled by the transport of the most mobile, long-lived fission products. For example, the Yucca Mountain PA considered colloid-facilitated transport for several actinides. The source terms for actinides at the waste form were generally very low, partly because of sorption on immobile corrosion products, which muted the response of these species at the accessible environment. In reducing environments, and environments with limited water flow (clay and salt), this result should be even more pronounced. Granted there is likely to be a dependence on the regulatory time period of interest, with longer time periods likely leading to greater importance of actinides and the model of transport assumed for these radioelements. Nevertheless, mobile dissolved species tend to control the overall dose projections.

The experience base of actinide transport in the environment for sites contaminated with radioactive waste lends credence to this result. In the US, risk assessments at sites such as Hanford, Los Alamos National Laboratory, Nevada National Security Site (formerly the Nevada Test Site), and the Savannah River Site all result in mobile species (radionuclides and other contaminants) in aqueous phases being the predominant risk drivers, rather species transported as colloids. For example, the Rocky Flats site dealt extensively with the issue of plutonium transport, and eventually analysts reached the conclusion that a sufficient understanding existed for the relevant mechanisms to dismiss any mode of transport of plutonium via groundwater in the risk assessment [37].

While work in colloid transport continues, there is a growing consensus that while very small quantities of actinides, present in colloidal form, travel a considerable distance, the vast majority of the inventory remains very close to the source, as an immobile constituent [38; 39]. For example, sampling stations located up to 4 km downstream from the Mayak Production Association in Russia detected the presence of plutonium and other radioactive and chemical contaminants (neptunium, uranium, nitrate ion). Solubile and, thus, mobile constituents such as $^{238}$U and $^{237}$Np migrated readily to about 2 km from the source, to the extent that groundwater concentrations reached values of the same order of magnitude as the value at the source [39, Table 1]). In contrast, $^{239}$Pu/$^{240}$Pu concentrations downstream are present at these locations at levels some three to four orders of magnitude lower than the value of the source term. Similarly, $^{241}$Am, another actinide for which colloid-facilitated transport has been implicated in past studies, is present at these downstream locations at levels that are two to three orders of magnitude lower than the source. Similar behavior has been observed in Mortandad Canyon, Los Alamos National Laboratory [40]. The picture that emerges is one in which only a very small fraction of the inventory is mobile via colloids over large distances.

Alternative transport models have been developed to capture this behavior [41], and active experimental programs are being conducted to evaluate parameters and their influence on behavior. For our purpose, this discussion implies that over time, as knowledge increases, and more risk assessments of contaminated sites are published, the importance of the issue of colloid-facilitated transport in PAs is likely to lessen relative to today. The implication, for our purposes, is the conclusion that the perceived benefit of partitioning and transmutation on reducing uncertainty in colloid-facilitated transport of actinides will also lessen.

# 4. UNCERTAINTY IN ENGINEERED BARRIER AND INFLUENCE OF FUEL CYCLE

## 4.1 Approach

As with the evaluation of uncertainties in the natural barrier, an assessment of FEPs relevant to the EBS and the associated uncertainties was performed. FEPs used by UFD (Appendix C), related FEPs used for the proposed repository at Yucca Mountain, and international FEPs (e.g., NEA) were examined (Table 4-1).

**Table 4-1. Features, events, and processes related to the repository and package components of the engineered barrier system are similar for both the open and closed fuel cycles except for geochemical and thermal processes (Appendix C).**

| | | Nuclear Fuel Cycle Option | |
|---|---|---|---|
| UFD FEP | FEP Category | Open | Closed |
| 2.1.03 | Waste package degradation (e.g., general and localized corrosion) | Include | Include |
| 2.1.04 | Buffer/Backfill | Include | Include |
| 2.1.05 | Seals | Include | Include |
| 2.1.06 | Other EBS materials (e.g., liner and supports) | Include | Include |
| 2.1.07 | Mechanical processes (e.g., rockfall, creep) | Include | Include |
| 2.1.08 | Hydrologic processes (e.g., advective and capillary flow through EBS backfill and seals) | Include | Include |
| 2.1.09.00 | Drift chemical processes | | |
| | Chemistry of water seeping into drift and backfill and chemical interaction with EBS material) | Include | Include |
| | Solubility | Include solubility of actinides and fission products | Include solubility of fission products |
| 2.1.09.50 | Transport chemical processes | | |
| | Advective and diffusive transport | Include transport of actinides and fission products | Include transport of fission products |
| | Sorption | Include sorption of actinides and fission products | Include sorption of fission products |
| | Complexation with organics | Exclude | Exclude |
| | Complexation with carbonates | Include carbonate complexes for actinides, fission products | Include carbonate complexes for fission products |
| | Colloid stability | CSNF colloids unstable at neutral pH but natural and corrosion products stable | Exclude |
| | Colloid-facilitated transport including advection, diffusion, and filtration | Include for actinides | Exclude |
| 2.1.10 | Biological processes (microbial activity) | Include through multipliers on degradation of package | Include through multipliers on degradation of package |
| 2.1.11 | Thermal processes (e.g., thermal effects on package, backfill, drift wall) | Include | Include (depending on repository design, lower temperatures or heat effects over shorter period) |
| 2.1.12 | Gas sources and effects (anoxic corrosion of package and organic material) | Include for salt and clay/shale repositories | Include for salt and clay/shale repositories |
| 2.1.13 | Radiation and radiolysis effects | Exclude | Exclude |
| 2.1.14.01 | Nuclear criticality in EBS and near field | Exclude for actinides | Exclude |

A major difference between the EBS and the NBS, as defined in this report, is the importance of FEPs relating to thermal processes because of the proximity of the EBS (e.g., waste package, buffer, backfill, seals) to the heat-generating waste form.[18] Hence, two aspects relevant to advanced fuel cycles are considered: (1) removal of actinides from the waste, and (2) the removal of high heat-generating waste from the system. We first discuss these two aspects relevant to FEPs. Second, we discuss system management aspects of the removal of major heat-generating radionuclides of the waste.

## 4.2 Evaluation of Features, Events, and Processes

The repository/package FEPs can be grouped into six broad categories (Table 4-1):

1. Repository/package integrity including (a) waste package degradation, (b) degradation of buffer/backfill/seals and other material of repository/package, (c) biological processes enhancing degradation of repository/package components, and (d) mechanical processes influencing EBS performance

2. Hydrologic processes impacting the repository/package

3. Geochemical and transport processes impacting movement of radionuclides through the repository/package, including (a) conditions of water entering the repository/package, (b) radionuclide speciation and solubility, (c) complexation, (d) sorption, and (e) colloid stability and transport

4. Thermal processes affecting repository/package components

5. Gas sources and effects

6. Radiation effects and nuclear criticality in the repository/package

For these six broad FEP categories, we discuss three aspects: (a) the impact on the technical basis to include or exclude a FEP in models of the disposal system for the analysis, (b) the effort to include the FEP in the modeling system and impact on modeling uncertainty, and (c) the effort to characterize the parameter uncertainty related to a FEP if included in the analysis. As described below, only (3) geochemical and transport processes influencing movement of radionuclides and (4) thermal processes are relevant in regards to the impact of alternative fuel cycles on the uncertainties associated with the EBS.

### 4.2.1 Thermal Processes

FEPs related to thermal effects on other EBS components must be included and parameters characterized. Repository dry-out is driven by waste heat, as are the peak temperatures reached at each EBS location. Lower temperature waste packages will impact thermally driven flow (convection) in the drifts and in waste packages, as well as two phase buoyant flow (heat pipes) in the near-field of the natural barrier.

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[18] As defined by the NRC [7], the "*engineered barrier system* means the waste packages, including engineered components and systems other than the waste package, and the underground facility" where the "*waste package* means the waste form and any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container" and where "*underground facility* means the underground structure, backfill materials, if any, and openings that penetrate the underground structure (e.g., ramps, shafts, and boreholes, including their seals)." However, we have included most of the thermally perturbed portion of the host rock with the EBS (e.g., 100 m around a disposal borehole) to avoid tedious repetition of factors related to the NBS and EBS, and we have excluded the waste form to focus attention on alternative forms in a separate chapter of the report.

The thermal effects on the EBS could be reduced if the heat load is significantly reduced for the closed fuel cycle; however, only for a closed fuel cycle with very extensive partitioning of many of the hot fission products could the modeling components in the EBS omit temperature effects. For example, if the waste management system so chose, peak temperatures on the waste package could be reduced such that corrosion at the high temperatures could be reduced. In those crystalline environments where a robust package is an important barrier for the geologic disposal system, this reduction in temperature might be sufficient to allow reduction of the package thickness. Yet, this option could also be pursued for the open fuel cycle by reducing the capacity of the package.

It is more likely, however, that overall repository temperature peaks, and the uncertainty associated with these peaks, would remain unchanged. To elaborate, thermal effects on performance uncertainty is typically limited by setting a design constraint on thermally sensitive components such that the uncertainty can be tolerated, as confirmed through experiments and modeling of the coupled thermal-hydrologic processes. That is, if a component of the disposal system (such as waste form, package, or geologic medium) degrades rapidly or changes properties above a certain temperature threshold, then a thermal constraint (such as on peak package and peak host rock temperatures) can be established with an appropriate safety margin, using, for example, the worst-case design basis heat load for the wastes and bounding thermal properties. An engineering strategy, such as minimum waste package and drift spacing, can then be adopted such that the repository does not exceed the thermal design constraints. Regardless of the engineering strategy chosen, the project would still have to evaluate coupled thermal processes to evaluate the behavior and uncertainty of the thermal constraints.

As noted in Chapter 2 and Figure 2-2 (Curve D), a likely response of the waste management system to a reduction in the inventory of heat generating actinides would be to increase waste loading and/or reduce waste package spacing to approach previously established thermal design constraints for the geologic disposal system (i.e., change the repository design). Provided the various thermal design constraints are met with similar margins of safety, it follows that the performance of a repository will be similar in relation to degradation of the packages, performance of the buffer, and behavior of the near field. It also follows that any scenario, model, or parameter uncertainty associated with thermal behavior of the repository would be similar. [19] Rather, the influence of an advanced fuel cycle would be primarily on the cost to the waste management system to meet the thermal design constraints relative to other engineering strategies, such as surface storage cooling, package loading, and repository layout, or potentially on repository capacity if area is constrained. Further discussion of the possible response of the waste management system to actinide and heat generating fission products is discussed further below in Section 4.3.

### 4.2.2 Engineered Barrier System Integrity and Mechanical Processes

#### *4.2.2.1 Included FEPs*

The important FEPs to be included that relate to the repository/package integrity and mechanical processes of the EBS (e.g. general and localized corrosion) are unchanged when actinides are removed from the waste form (Table 4-1). Early failure of the waste package, general and localized corrosion, stress corrosion cracking, hydride cracking, and microbial influenced corrosion are not a function of the waste form content. Whether the waste package temperature is ever above or remains below the boiling point of water, corrosion processes do not occur until after water returns to the waste package surface (in the form of deliquescence from humid air in salts on the package surface initially or infiltrating water

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[19] With reprocessed HLW, it is possible to load packages such that peak temperatures of the package surface are initially much higher but decay to low temperatures faster than for SNF, such that overall peak temperatures in and around the repository are similar but last for a shorter time.

later). These processes are the same in the cases of open cycle SNF and HLW and closed cycle HLW. Only the time of occurrence would likely change because of the different thermal decay history.

The influence of microbial processes on degradation of the waste package have previously been represented by multipliers which are not impacted by waste form inside the package or removal of high heat via an alternative fuel cycle.

#### *4.2.2.2 Modeling Uncertainty*

The uncertainty in the number and location of general corrosion breaches would not change significantly. Furthermore, uncertainties related to the number, type, and location of early-failed waste packages would not significantly change for waste packages containing waste from a full recycle process.

#### *4.2.2.3 Characterization of Parameter Uncertainty*

Uncertainties associated with the corrosion rate parameters of waste package material are likely unaffected by the presence or absence of actinides. Rather, the uncertainty in the parameter values will be a function of the underlying data. Provided the package cycles through the same temperature range, with and without actinides (due to a corresponding change in waste loading and package spacing), then the same level of uncertain in results will be produced; albeit, at different times because the uncertainty time profile of the result would change because of the different thermal history.

### 4.2.3 Hydrologic Processes

Hydrologic processes in the repository/package component of the EBS (including those relating to flow through the EBS, alteration and evolution of flow pathways, relative humidity and condensation formation in the repository, and capillary effects) will not be directly influenced by the actinide content directly but will be affected by the temperature in the EBS, which is discussed above for thermal processes and is discussed below for waste management.

### 4.2.4 Geochemical and Transport Processes

#### *4.2.4.1 Included FEPs*

Except for FEPs related to colloid-facilitated transport (discussed in Chapter 3 for the natural system), all FEPs related to geochemical and transport process would be included regardless of the fuel cycle (Table 4-1). The chemical characteristics of water in the backfill and tunnels, the chemical interaction of water with corrosion products and backfill, and the chemical effects at the EBS component interfaces are dependent on the temperature of the EBS region. However, they are included regardless of the temperature.

#### *4.2.4.2 Characterization of Parameter and Modeling Uncertainty*

Except for FEPs related to colloid-facilitated transport (discussed in Chapter 3 for the natural system), characterizing the uncertainties and including them in models will still be necessary for FEPs related to geochemical and transport processes influencing movement of radionuclides through the EBS. Certainly, the characterization of the dissolved concentration limits of radionuclides could be simplified by removal of actinides. Yet, the effort to characterize uncertainty is not completely eliminated. FEP exclusion arguments, based on some type of limited characterization, would still have to be made showing that the very small amounts of actinides and other radionuclides remaining from a less than perfect separation process are not important to the PA.

### 4.2.5 Gas Sources

Potential gas sources include (a) anoxic corrosion of metal of the package or metals in the SNF, and (b) organic material in the EBS. The importance of gas sources depends upon the repository environment with the impermeable clay/shale and salt repositories possibly including the effects on the reduced rate of the creep closure of the repository and with crystalline repositories having sufficient advective flow usually excluding these FEP categories. The absence of metal associated with SNF and any organics in the EBS would simplify characterization of parameter uncertainty, but removal of all gas sources may not be possible, in which case, the modeling components would still be necessary in the PA.

### 4.2.6 Radiation Effects and Criticality

In the case of radiation effects, radiolysis (alpha, beta, gamma, and neutron) may occur, leading to the production of charged and uncharged species (radicals) that can influence water chemistry, radionuclide speciation, and redox potential. Radiation damage can also occur in EBS components such as waste package and buffer. Although these processes have been excluded in the past, removal of actinides would simplify the exclusion arguments.

Criticality may result from degradation of internal structures within the waste package, or of the waste package itself. Criticality is not simply limited to the waste form or waste package; near-field criticality in the EBS may also occur if fissile material is transported by liquid or vapor movement and concentrated in a given area and geometry of the EBS. Criticality was excluded even for the large packages proposed at Yucca Mountain [42], and repository concepts in crystalline, salt, and clay/shale would likely require smaller packages with less potential for criticality. None the less, the argument for excluding criticality would be trivial without uranium, plutonium, and other minor actinides present.

## 4.3 Influence on the Waste Management System

Prior studies have discussed the influence of advanced fuel cycles on thermal management (e.g., [3]) and were summarized by the NEA report discussed in Chapter 1 [2]. This report section synthesizes this work from the point of view of the US waste management system.

Repository designers typically begin with a prescribed waste stream, geologic medium, and regulations that limit the risk (dose) to the public over a long period of time. The waste stream information includes both the characteristics of the waste (radionuclide content and physical form) and the amount of the waste to be disposed (the repository capacity). The capacity can be based on the overall amount projected to be accumulated nationally, or on some part of that amount (e.g., the Nuclear Waste Policy Act limits the first repository to 70,000 MTHM until a second repository is operational). If a particular site, design, and waste form result in predicted performance that approaches the regulatory limits on individual dose, for either nominal scenarios or for disruptive event scenarios, the repository capacity could be set at a level below the national total waste inventory or a legally prescribed portion of that inventory. Predicted repository performance includes the model form, parameter, and scenario uncertainties discussed in Chapter 2. Uncertainties are treated in a manner prescribed by regulation, and performance values that are compared to regulatory limits are typically mean values of probabilistic calculations in a PA.

Because nuclear waste produces significant amounts of thermal energy over an extended period of time, repository designers set temperature limits for one or more components of the engineered barriers and natural system of a repository, to avoid undesirable phenomena and to ensure those engineered components and the natural system are modeled within the valid ranges of the scenarios, conceptual models, and parameters included in the PA. A key part of the repository design is to develop a system that meets the thermal limits in a reasonable sized footprint and at a reasonable cost. Thus, the repository designer develops the design from both thermal performance and dose performance points of view.

Experience to date indicates that design concepts that use a safety approach that contains the waste for long periods and then limits its transport over even longer periods can meet the dose limits with significant margin, for both nominal scenarios and disruptive event scenarios. In that case, the designer can consider the influence of design choices on the trades between thermal performance and the repository footprint size and total system lifecycle cost. The following discussion considers the influence of advanced fuel cycles (i.e., the waste stream) on these thermal and cost trades, from the point of view of the overall waste management system.

To begin the discussion, consider the potential benefits of separating radionuclides into multiple waste streams, which is a side benefit of advanced fuel cycles that reprocess used fuel to recover unused fissile atoms for reuse in reactors that can extract additional productive energy from them. The natural divisions between the waste streams are associated with half-life and thermal output. Radionuclides with half-lives of decades to centuries can be disposed by methods that need containment and slow transport performance for times much shorter than geologic periods. Engineered barriers can be relied upon for a greater extent because the facility lifetime is comparable to experience with engineered systems. Radionuclides with half-lives of millennia to millions of years, on the other hand, will not fully decay away within the performance periods of engineered barriers, even allowing that some designs project extremely long-term performance of those engineered systems. One must allow for disruptive events, beyond-design-basis situations, and the inherent uncertainties in such long-term performance, and hence a geologic repository that includes both engineered containment and slow transport in the natural system is necessary for long half-life radionuclides, to limit individual dose.

The natural categorization between long and short half-life radionuclide disposal requirements is not so simple, however. Reprocessing is designed to extract unburned fissile elements, and partitioning the remaining radionuclides according to half-life is not straightforward. Elements with both long and short half-life isotopes must be placed in the long half-life repository because chemical reprocessing cannot separate isotopes of the same element. Further, reprocessing designs are selective to separating groups of elements from each other, based on chemical activity, and further separation of elements would involve additional process steps.

In addition to the capability of disposing of short-lived radionuclides in non-geologic disposal systems, the ability to reprocess UNF into several waste streams (besides new fuel elements) creates the opportunity to sequester single elements in a separate disposal system or in enhanced engineered barriers in the geologic repository used for the long-lived radionuclides. Technetium is one element that has been discussed in this regard.

For the purpose of discussion here, we assume that the waste management system designer has the option of partitioning the waste stream into multiple categories for the purpose of improving the effectiveness or cost of the national waste management stream. Such partitioning could significantly reduce the thermal output of the waste stream(s) destined for a geologic repository.

Wigeland, et al., [3] used an existing repository design in tuff to explore the relationships between partitioning and repository capacity. They studied the waste loading (MTHM/m) allowable within the repository design thermal limits, for three segregation approaches (removing Cs/Sr, removing Am/Pu, and removing Am/Pu/Cm). For each approach, they considered residual material in the waste parametrically (10%, 1%, and 0.1%). Their results are summarized in Table 4-2.

The table shows that removing Pu/Am provides about five times the waste per meter of drift, within the thermal limits, if the other repository parameters (such as drift spacing, closure time, or ventilation rate) are unchanged. As Pu/Am residual amounts decrease, the controlling temperature limit shifts from the mid-pillar location between drifts (and at times later than 1000 yr), to the drift wall at closure time when ventilation ceases. On the other axis, removing Cs/Sr provides little benefit if the Pu/Am is not removed. When both sets of radionuclides are removed at high efficiency, the allowable waste per m increases to about 40 times that for once-through fuel, and the controlling temperature limit is the drift wall shortly after emplacement time.

**Table 4-2. Increase (multiplier) in drift loading in a tuff repository for different levels of Cs/Sr and Pu/Am in the waste composition. The results are normalized to values for disposal of waste from the current once-through fuel cycle (i.e., no separation of radionuclides)**

| | 100% of Pu/Am in waste | 10% of Pu/Am in waste | 1% of Pu/Am in waste | 0.1% of Pu/Am in waste |
|---|---|---|---|---|
| 100% of Cs/Sr in waste | 1.0 | 4.3 | 5.3 | 5.4 |
| 10% of Cs/Sr in waste | 1.0 | 9.6 | 26.0 | 27.0 |
| 1% of Cs/Sr in waste | 1.0 | 10.0 | 39.0 | 40.0 |
| 0.1% of Cs/Sr in waste | 1.0 | 10.0 | 41.0 | 42.7 |

Assumptions: 50 GWd/MT burnup, separation at 25 yr out of reactor, emplacement at 25 yr out of reactor, closure at 100 yr out of reactor,15 $m^3$/s ventilation during operations prior to closure

Color codes: Red is limited by mid-drift temperature. Blue is limited by drift wall temperature at closure. Green is limited by drift wall temperature at emplacement

Wigeland, et al. [3] also considered removing Cm with the Pu/Am. The results were qualitatively similar, with the high efficiency removal of Pu/Am/Cm improving waste per meter to 5.7 times that of unreprocessed waste, and with high efficiency removal of both sets of radionuclides improving waste per m to 225 times that of unreprocessed waste.

Wigeland, et al. [3] also note that similar results were calculated for a lower temperature repository in the same geologic medium, and that other repository design parameters could be adjusted to further increase the repository capacity within the thermal limits. For example, if the drift wall temperature at preclosure is the controlling limit, repository capacity could be increase by decreasing drift spacing, which would reduce the margin to the mid-pillar limit without significantly changing preclosure drift wall temperatures.

For the present report, the authors considered similar strategies as in Wigeland, et al., [3]. An example of the quantitative reduction in thermal output is shown in Figure 4-1, which uses data from [43]. The figure shows the reduction in thermal output (W/MTHM) if Cs/Sr or if Cs/Sr/Ba/Rb/Y are removed by an advanced fuel cycle. The benefit diminishes with time due to the relatively short half-life of isotopes of these elements, as compared to the half-lives of some of the other constituents of the waste. For example, at 50 years out-of-reactor, the reprocessed waste (with Cs/Sr/Ba/Rb/Y) has only 50% of the thermal output of the original waste. However, at 100 years out of the reactor, the reprocessed waste would have as much as 70% of the thermal output of the original waste (Figure 4-1). As shown by Wigeland, et al. [3], removing Cs/Sr and Pu/Am reduces heat so much that waste volume, rather than heat will drive reactor layout and waste package capacity; the lower (green) curve is consistent with that result.

Wigeland, et al. [3] explored two sets of radionuclides, but limited the design changes to the waste package spacing in the tuff drift. The remainder of this section extends Wigeland's work to include other aspects of the repository design and waste management system design, for the situation where only Cs/Sr/Ba/Rb/Y are removed.

A number of potential benefits of reprocessing are possible for the waste management system. These are listed below, and evaluated using the thermal modeling tools described in [44]. The analysis began with the clay repository design [44, Fig. 5.2-7]. The clay repository design showed compliance with a 100°C thermal limit using 4-PWR spent nuclear fuel assembly (60 GWd/MTHM) waste packages stored with 10- m center to center axial spacing in boreholes that are spaced 30 m apart, and with a little more than 100 yr of surface storage prior to emplacement. For this analysis, a shorter surface storage time of 75 yr was used, resulting in a 131°C peak temperature at the interface of the waste package and the bentonite buffer. This peak temperature is near the upper end of the projected range of acceptable bentonite temperatures, based on ongoing technical work in the international community.

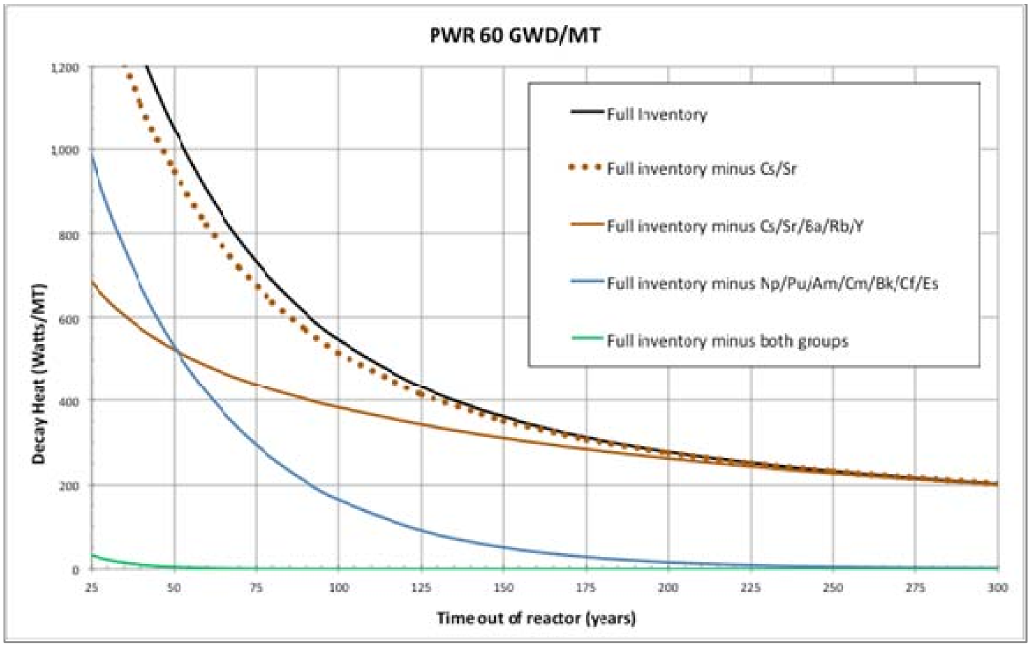

**Figure 4-1. Effect on waste heat during the thermally-dominated repository period for the full inventory and for several options of reprocessed inventory.**

- A sensitivity run used exactly the same repository design, but with reprocessed fuel in which Cs/Sr/Ba/Rb/Y have been removed. The resulting peak temperature was 95°C, more than 30°C less than the base case. The lower temperature could result in **exclusion or simplification of some FEPs.** For example, the cooler design could result in exclusion of some thermal coupled process FEPs and could reduce the complexity of testing and modeling needed to support models that include other thermal coupled process FEPs, as discussed in Section 4.2.
- The waste management system currently envisions surface storage at reactors, at centralized storage sites, or near the repository. This storage is for the purpose of waiting for radioactive decay to reduce the thermal output of the waste (per metric ton). If the waste stream to be disposed of in the geologic repository is thermally limited, reprocessed waste with less thermal output will require **shorter surface storage times** before emplacement. A sensitivity run used the reprocessed fuel with a very short surface storage time (including time in the reactor fuel pool) of only 20 yr, and resulted in the same peak temperature (131°C) as the base case. Thus, 55 yr of surface storage costs could be avoided if the fuel were reprocessed.
- If the repository has significant performance (risk, dose) margin for unreprocessed waste, it could accommodate additional waste (repository capacity) within its regulatory limits. **Repository(s) with larger capacity** translate to **fewer repositories in the waste management system**, and that translates to significant capital cost savings and even more significant reductions in licensing, siting, and community interaction. Larger capacity can be obtained via **reduced spacing between waste packages**, or using **larger waste packages**.
- A sensitivity case was run with reprocessed fuel in the same capacity waste packages, and with the same surface storage time, as the base case. Spacing between waste packages was reduced to

6 m axially (a fraction of a meter gap between packages), and lateral borehole spacing was reduced to 19 m. The result was the same peak temperature (131°C) as the base case, but with 2.63 times as much waste in the same footprint.

- A sensitivity case was run with reprocessed fuel in waste packages with the same axial and lateral spacing, as the base case. The waste package size was increased to 8 HLW canisters (the same size as an SNF assembly, to simplify the calculation, in a 3 × 3 configuration with the central position being empty or used to dispose of non-heat-generating waste). To reach the same peak temperature (131°C) as the base case, the surface storage time was increased to 120 yr. Thus, an economics tradeoff could be made between the added costs of 45 yr of additional surface storage time versus cost savings due to twice the waste in the same footprint. An additional sensitivity case used an intermediate surface storage time of 100 yr, with a peak temperature about 7°C higher than the base case. This case would involve a more complex economics tradeoff between the added costs of 25 yr of additional storage time and reduced costs based on twice the waste in the same footprint, with additional licensing risk of the slightly higher peak temperature.
- Some geologic repository designs use ventilation for decades to centuries after emplacement, to remove most of the heat from the waste, and thereby to limit the temperature rise of the engineered barriers and the near-field of the natural system. Reprocessed waste with less thermal output could require **less (or even no) ventilation flow for shorter periods of time**, which will reduce cost and permit earlier closure of the repository. No sensitivity case was run for this metric because the long ventilation periods largely are during the time that the thermal output curves are similar.
- The reprocessed waste stream of short-lived elements that are not destined for a geologic repository is to be disposed of in a near-surface facility using appropriate engineered barriers. It could be possible to **co-locate the near-surface facility (and perhaps a centralized storage facility as well) with the reprocessing facility**. This would benefit from an economy of scale perspective, using shared security infrastructure, for example. In addition, it may be possible to **harvest process heat from the short-lived radionuclides** during their decay period if they are collocated with an industrial facility such as a reprocessing plant.

The fission product (Cs/Sr/Ba/Rb/Y) removal will include long-half lived Cs-135 and Rb-87. Thus, it may be necessary to move the fission products from the engineered few-century repository to the geologic repository after the heat decays to low levels. It could then be packed efficiently into space reserved for it.

The Fuel Cycle Options campaign is currently developing a set of analyses of a wide range of fuel cycles that include multiple reactor types and reprocessing methods. The tradeoffs described above for a single reprocessing case and single reactor type are illustrative of how the Waste Management System can be integrated into the overall Fuel Cycle Option analysis.

# 5. UNCERTAINTY IN WASTE FORM AND INFLUENCE OF FUEL CYCLE

## 5.1 Approach

Although the waste form is often considered part of the EBS, this report discusses the waste form separately and so a FEP list was compiled specifically for the waste form from EBS FEPs used by UFD (Appendix C) (Table 5-1).

**Table 5-1. Features, events, and process related to the waste form are similar for both the open and closed fuel cycles except for geochemical and transport processes (Appendix C).**

| | | Nuclear Fuel Cycle Option | |
|---|---|---|---|
| UFD FEP | FEP Category | Open | Closed |
| 2.1.01 | Inventory | Include activity of actinides And fission products | Include activity of fission products |
| 2.1.02 | Waste form degradation | Include CSNF UOX and CSNF U carbide | Include HLW Electrochemical (EC)-ceramic,<br>HLW EC- metal, and<br>HLW borosilicate glass |
| | | Include zircaloy cladding,<br>Silicon carbide | |
| 2.1.09.00 | In-package chemical processes | | |
| | Solubility | Include solubility of actinides and fission products | Include solubility of fission products |
| | Complexation with carbonates | Include complexation of actinides and fission products | Include complexation of fission products |
| | Complexation with organics | Exclude | Exclude |
| | Colloid formation | Include colloids from CSNF, EBS corrosion and natural barrier | Exclude (colloids from HLW glass but no actinides) |
| | Colloid stability | CSNF colloids unstable at neutral pH but natural and corrosion products stable | Exclude |
| 2.1.09.50 | Transport chemical processes: Sorption | Include sorption of actinides and fission products | Include sorption of fission products |
| 2.1.10 | Biological processes (microbial activity) | Include through multipliers on degradation of waste | Include through multipliers on degradation of waste |
| 2.1.11 | Thermal effects on waste | Include | Include (depending on repository design, lower temperatures or heat effects over shorter period) |
| 2.1.12 | Gas sources and effects (fission product gas) | Include for salt and clay/shale repositories | Include for salt and clay/shale repositories |
| 2.1.13 | Radiation and radiolysis effects | Exclude | Exclude |

## 5.2 Evaluation of Features, Events, and Processes

Four categories of FEPs (many similar to the FEPs for EBS) are usually included and modeling components are developed for the waste form (Table 5-1):

1. Inventory of actinide and fission products

2. Waste form degradation, including (a) CSNF waste form and cladding degradation, (b) HLW degradation, (c) biological processes enhancing degradation

3. Thermal effects on waste form degradation

4. Geochemical and transport processes, including (a) in-package chemistry, (b) radionuclide speciation and solubility, (c) complexation, (d) sorption, and (e) colloid stability and transport

For FEPs related to gas sources, the decision to include or exclude depends upon the disposal environment with the very impermeable clay/shale and salt repositories including the effects and crystalline repositories excluding the FEP categories.

5. Gas sources

Finally, other categories must be considered but are excluded:

6. Radiation effects

As with the other system components, three aspects of characterizing uncertainty are pertinent here: (a) the impact on the technical basis to include or exclude a FEP in models of the disposal system for the analysis, (b) the effort to include the FEP in the modeling system and its impact on modeling uncertainty, and (c) the effort to characterize the parameter uncertainty related to a FEP if included in the analysis. Only FEPs related to colloid-facilitated transport of the fourth category, geochemical and transport processes would be excluded because of actinide removal. The other two aspects are discussed below.

### 5.2.1 Inventory

An advanced fuel cycle with partitioning and transmutation of actinides would reduce somewhat the characterization of uncertainty necessary for inventory, because parameters for actinides would be absent. Yet, it would not eliminate the need for the modeling components because fission products would still be present. The influence of pyrophoric uranium hydride and uranium metal reactions with oxygen and water present inside the waste package and production of flammable gases in U-Th carbide and Pu-U carbide fuels have typically been excluded but removal of uranium as part of reprocessing would make arguments for excluding these effects trivial.

Two types of releases take place from SNF (a) a prompt release, which takes place as soon as the cladding is breached (or when a package is breached if all the cladding is assumed failed as in the total system performance assessment conducted for the license application for Yucca Mountain (TSPA-LA), and (b) a degradation release, which takes place as the fuel matrix degrades. Hence, reprocessing of the fuel, regardless of the removal of actinides, removes this small fraction of the inventory that could be promptly released. Fission products and corresponding central-tendency fractions of the inventory included in TSPA-LA are $^{90}$Sr, (0.0009) $^{99}$Tc (0.0010), $^{129}$I (0.11), $^{137}$Cs (0.036), and the activation product gas 14C (0.08). Although the values are uncertain, they are not important in explaining the spread in dose results (Appendix B), and so even this indirect effect of processing would not materially influence uncertainty of dose.

### 5.2.2 Waste Form Degradation Rates

Regarding FEPs related to waste form degradation, a HLW waste form offering better performance relative to borosilicate glass or zircaloy clad SNF could potentially be developed along with either the current open fuel cycle or as part of a future advanced fuel cycle. However, new waste forms do not always produce substantially better disposal system performance, because often other components of the multiple barrier disposal system compensate for less favorable characteristics of the borosilicate glass or zircaloy-clad SNF as observed in UFD demonstration calculations for clay/shale repository environments and at Yucca Mountain in the oxic environment (Appendix D).

Furthermore, new waste forms require extensive characterization of uncertainty, which would increase the burden, at least initially, rather than decrease the burden, especially, for advanced fuel cycles that produce multiple waste streams and multiple waste forms. In other words we are replacing the current characterization of performance and uncertainty related to borosilicate glass or zircaloy-clad SNF with the future characterization of performance and uncertainty of the new waste form. As further discussed in Appendix D, new waste forms do not automatically produce better disposal system performance in a multiple barrier disposal system.

In general, flexibility has been an attribute of disposal system designs rather than finely tuning the repository design to specific characteristics of the waste form. Flexibility is a natural outcome of using multiple barriers in the geologic disposal system. Current geologic disposal systems have been designed for direct disposal of SNF only (Sweden in crystalline rock), for HLW only (France in clay/shale), and for a mixture of SNF and HLW (US in volcanic tuff [13]).

In relation to disposal system design, NRC stated for the proposed Yucca Mountain repository (and presumably for future repositories) [7, p. 55758]

> …Consistent with the Commission’s risk-informed and performance-based regulatory philosophy, DOE is provided flexibility for deciding the extent and focus of site characterization. As the repository designer, DOE may place greater or lesser reliance on individual components of the repository system when deciding how best to achieve the overall safety objective.

In other words, the licensee has the flexibility, informed by the important uncertain parameters and models identified in the PAs, to “place greater or lesser reliance on individual components of the repository system.” Thus, high uncertainty of, for example, a current (or new) waste form, is not considered a detriment to repository performance provided overall safety was achieved with other barriers.

### 5.2.3 Thermal Effects

As described in detail for the repository/package component of the EBS, the thermal effects on the waste form could be reduced if the waste loading was significantly reduced for the closed fuel cycle. However, only for a closed fuel cycle with very extensive partitioning of many of the hot fission products could the modeling components in the EBS omit temperature effects. It is more likely, however, that the overall repository temperature peaks and the uncertainty associated with these peaks from thermal processes would remain unchanged.

### 5.2.4 Geochemical and Transport Processes

The in-package chemistry is insensitive to the incoming water composition and, instead, is influenced largely by the degradation reactions of the waste form and waste package, and with the secondary minerals that precipitate [45; 46]. The borosilicate glass of HLW can produce somewhat more basic conditions (for example, range of 5.3 to 8.3 for SNF packages versus 5.3 to 9.1 for HLW packages at Yucca Mountain), but not substantially greater dissolution of radionuclides.

An advanced cycle would reduce somewhat the characterization of uncertainty necessary for solubility, and sorption because parameters for actinides would not be present. Yet, it would not eliminate the need for the modeling components because fission products would still be present. Also, some characterization of uncertainty would be needed to show that the very small amounts of actinides and other radionuclides remaining from a less than perfect separation process are not important to the PA, as previously mentioned. Radionuclide speciation and solubility are affected by the presence of uranium and actinides. Furthermore, modeling of secondary phase effects of uranium, including co-precipitation, as well as neptunium inclusion in uranium mineral precipitates or corrosion products, would be simplified if actinides were absent.

Modeling components for formation and stability of colloids for colloid facilitated transport within the EBS would not be necessary in the absence of actinides.

### 5.2.5 Gas Sources

Potential gas sources include helium from alpha decay of actinides ($^{244}$Cm, $^{238}$Pu, $^{239}$Pu, $^{240}$Pu, and $^{241}$Am) within the SNF The importance of gas sources depends upon the repository environment with the impermeable clay/shale and salt repositories possibly including the effects on the reduced rate of the creep closure of the repository and with crystalline repositories having sufficient advective flow usually excluding these FEP categories. The absence of actinides associated with SNF would simplify characterization of parameter uncertainty, but removal of all gas sources in the EBS may not be possible, in which case, the modeling components would still be necessary in the PA.

### 5.2.6 Radiation Effects

Decay-derived helium gas pressurization, and gases formed through alpha-radiolysis of water vapor are uncertainties that can be excluded if actinides are removed from the waste form.

# 6. Findings and Suggested Modeling Activities

Development and implementation of advanced fuel cycle technologies, including partitioning and transmutation, will impact storage, transportation, and disposal of the waste management system. This report evaluates the impact on the geologic disposal system.

## 6.1 Key Points

For the undisturbed scenario, the natural barrier system in reducing environments, coupled with the engineered barrier system, greatly reduces the mobility of actinides, such that fission products, which exist in all fuel cycles, dominate the hypothetical dose to individuals $10^4$ to $10^6$ yr in the future. Hence, removal of actinides from the repository would not change the magnitude of the mean dose.

For disruptive scenarios, changes in actinide inventory cannot change the inherent uncertainty of the event, but as a secondary effect, extensive disruption of the engineered barrier system can result in more actinide releases. Although dose might decrease somewhat with the removal of actinides, the probability-weighted dose is already so small for inadvertent human intrusion, and possibly for natural disruptions as well, that use of an advance fuel cycle to further decrease these already insignificant doses would not be warranted.

Because geologic disposal is required for fission products regardless of the fuel cycle, the issue of importance is whether removing actinides provides a noticeable *incremental* decrease in the spread (uncertainty) of dose. However, the spread of dose is usually caused by parameters unrelated to the characteristics of actinides; specifically, parameter uncertainty associated with the natural barrier. In addition, a few parameters of the waste package of the engineered barrier system can contribute to the spread of the dose, (particularly in disposal environments in which advective releases provide an important contribution to total dose).

Processes and associated parameters directly related to actinides have only a weak influence on the spread of the dose. The most obvious process is colloid-facilitated transport of actinides, but because actinides are not the primary contributors to dose in most environments, the uncertainty associated with colloid-facilitated transport of actinides is muted. Furthermore, any remaining uncertainty specifically associated with fission products is not necessarily less than the uncertainty associated with actinides. Hence, the spread of dose results will not be significantly reduced by the removal of actinides in the inventory.

The engineered barrier system design would likely change (repository area reduced and/or container capacity increased) to meet previously established design constraints on thermally sensitive components for waste produced by an advanced fuel that has lower thermal output. Hence, any scenario, model, or parameter uncertainty associated with thermal behavior of the repository would be similar, provided the thermal design constraints are met with similar margins of safety with and without the presence of actinides. Rather, the influence of an advanced fuel cycle would be primarily on the cost to the waste management system to meet the thermal design constraints relative to other engineering strategies that influence thermal behavior, such as surface storage duration, waste package capacity, repository layout, and repository capacity (if area is constrained).

The characterization of natural and engineered barrier uncertainty is a major task of a performance assessment for a geologic repository. This task remains a major effort regardless of the fuel cycle. Granted, parameter characterization and modeling components for formation, stability, and transport of colloids would be unnecessary in the absence of actinides. Also, removal of actinides would somewhat diminish the characterization of parameter uncertainty related to inventory, solubility, and sorption because of their absence, but some characterization would be necessary to support screening out the importance of remnant actinides in the less than perfect separation. Furthermore, the modeling components would still be necessary and the associated modeling uncertainty would still be present for the fission products.

Any of the small benefits of reducing uncertainty from actinide removal described above would potentially be offset by the need to characterize new waste forms (either HLW or advanced fuels). As an example, in the case of HLW disposed in a new ceramic waste form, the applicant under the Yucca Mountain regulations (10 CFR 63) (and presumably future regulations) would need to (a) "provide the technical basis for either inclusion or exclusion of features, events, and processes" on various modes of failure and degradation. (b) "consider alternative conceptual models" that explain modes of degradation, and (c) "account for uncertainties and variabilities in parameter values" for the mathematical models developed for the performance assessment.

Furthermore, any of the small benefits of actinide removal would only be realized in the situation where current nuclear fuel from the open cycle is stored and then fully reprocessed when an advanced fuel cycle with actinide partitioning and transmutation is fully implemented in the future. Any transition period in which one or more repositories are built to handle SNF and HLW from the open cycle or a transition open cycle would necessitate the characterization of uncertainty and inclusion of modeling components related to actinides.

Therefore, the UFD Campaign can reasonably conclude that advanced fuel cycles, in combination with partitioning and transmutation, which remove actinides or that use advanced fuels, will not significantly alter (1) the repository performance, (2) the spread in dose results around the mean, (3) the modeling effort to include significant FEPs in the performance assessment, or (4) the characterization of uncertainty associated with natural or engineered barriers of a geologic disposal system in the regulatory environment of the US. This finding ultimately rests on the fact that the influence of uncertainty in waste form behavior is diminished because other barriers often control the release, whether by design in the case of a robust waste package or by existing geochemical conditions in the natural barrier. In other words, the combination of the natural and engineered barriers provides a geologic disposal system that mitigates the unknowns of scenario uncertainty and model uncertainty and provides sufficient flexibility to accommodate a large variety of radioactive wastes from existing commercial reactors, experimental reactors, and reprocessed fuel from future fuel cycles.

However, as the Fuel Cycle Technology Program pursues the development of sustainable fuel cycles, the UFD Campaign should continue to anticipate that nuclear fuel cycles that remove short-lived, heat-producing radionuclides and long-lived actinides will have a significant impact on the engineered barrier of a repository (e.g., layout and waste package spacing), waste package (volume and heat load) as well as the overall waste management system (influencing, for example, surface storage duration).

## 6.2 Suggested Future Modeling

The key findings reached above, as gleaned from past studies, would benefit from quantitative analyses to refine the points discussed with respect to uncertainties. The following list describes some suggested analyses.[20]

### 6.2.1 System Wide Analysis

Use the UFD generic performance assessment models in sensitivity analyses for each of the four geologic disposal concepts (salt, clay, and granite repositories, and deep borehole disposal) to compare behavior of (1) SNF from the current open cycle using conventional zirconium-clad uranium-oxide fuel from light water reactors or silicon carbide fuel from high temperature gas reactors with (2) theoretical closed fuel cycles disposing HLW to illustrate the effects of removing actinides under undisturbed, inadvertent human intrusion, and plausible natural disturbances. These studies should include all waste forms that may need geologic disposal even if separated from other waste (e.g., iodine).

### 6.2.2 Engineered Barrier System Studies

Develop disposal approaches that take advantage of the partitioning of radionuclides into multiple forms in an advanced fuel cycle. Different radionuclides are important to thermal performance than those important to total system performance. Using this information could result in a compact repository for the long-lived radionuclides and a separate area for thermally important radionuclides.

### 6.2.3 Waste Form Studies

Compare performance of current waste forms to potential performance of several tailored waste forms from the closed fuel cycles to evaluate potential benefits.

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[20] Refer to the UFD R&D roadmap for the many topics under consideration beyond the studies listed here to bolster understanding about geologic disposal uncertainty [34]

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# APPENDIX A: US STUDIES OF SYSTEM PERFORMANCE

Numerous studies have evaluated the influence of alternative fuel cycles on system performance and several reviews of those studies have been conducted as noted in the introduction [1; 2; 16]. Here, we summarize preliminary results from the UFD Campaign after reviewing current US regulations for geologic disposal systems.

## A.1 EPA Standard for Yucca Mountain Disposal System, 40 CFR 197

EPA in its 40 CFR 191 health standard and NRC in its implementing regulation 10 CFR 60 establish post-closure performance requirements, such as cumulative release over $10^4$ years for the disposal of wastes for a generic geologic repository. However, policies reflected in the more recent site-specific health standard, 40 CFR 197, and implementing regulation, 10 CFR 63, established for the Yucca Mountain disposal system have set precedent. Thus, it is likely that both NRC and EPA will consider these changes as other repository sites are evaluated.

### A.1.1 Standard for all Scenarios Except Human Intrusion

In 40 CFR 197, EPA provides limits to the Committed Effective Dose Equivalent (CEDE) for individuals located in the predominant direction of groundwater flow at the point of maximum concentration in the accessible environment beyond a controlled area. The boundary in the direction of predominant of groundwater flow and the nearest current community was $\leq\sim 18$ km and $\leq 5$ km in other directions from the perimeter of the emplaced waste. EPA set a dose limit of 15 mrem/yr (0.15 mSv/yr) for the maximum mean of the expected peak dose over a regulatory period of less than $10^4$ yr and 100 mrem/yr (1 mSv/yr) for times greater than $10^4$ yr up to geologic stability at Yucca Mountain ($\sim 10^6$ yr) (Table A-1).

**Table A-1 Regulatory basis for Yucca Mountain geologic disposal system in US.**

| Regulation | Requirement | Measure | Limit |
|---|---|---|---|
| 40 CFR 197 (YM) 2001, 2008 | 1. Individual Protection | Expected CEDE to reasonably maximally exposed individual (RMEI) for all retained scenario classes over $10^6$ yr | $<15$ mrem/yr for $t \leq 10^4$ yr<br>$<100$ mrem/yr for $10^4 < t \leq 10^6$ yr |
| | 2. Human Intrusion | Expected CEDE to RMEI for stylized circumstances (i.e., single intrusion into degraded package; borehole not carefully sealed such that radionuclides of package migrate through borehole to underlying aquifer) | $<15$ mrem/yr for $t \leq 10^4$ yr<br>$<100$ mrem/yr for $10^4 < t \leq 10^6$ yr |
| | 3. Groundwater Protection | Expected concentration in representative volume of groundwater for all scenarios for $^{226}$Ra/ $^{228}$Ra, α-emitters (including $^{226}$Ra but not U or Rn); and whole body dose from beta and photon emitters | $^{226}$Ra/ $^{228}$Ra < 5 pCi/L<br>α-emitters < 15 pCi/L<br>dose < 4 mrem/yr |
| 10 CFR 63 (YM) 2001 | 3. Requirements for PA | Requirement to describe technical basis of multiple barriers | |

The EPA also specified groundwater protection requirements (Table A-1). The groundwater protection requirements have not typically been a limit for repository performance and so demonstration calculations in the generic repositories have not yet been performed and this report has not considered them. The removal of uranium would eliminate $^{226}$Ra and $^{228}$Ra. However, the groundwater protection requirement could become more important if the US responded to the potential for cooler waste from advanced nuclear cycles and placed more waste in a container and more waste in any one repository in order to approach thermal constraints (the current agreement in the US is 70,000 MTHM for the first repository until another repository is operating) and, thereby, increase the concentration of fission products and potentially the concentration of beta and photon emitting radionuclides.

### A.1.2 Human Intrusion Standard

Because exposure to those inadvertently drilling into a repository was based on the inventory rather than on characteristics of the disposal system, EPA did not include a standard for exposure to the drillers. Furthermore, EPA and NRC did not include a standard for the public from subsequent dispersal of drill cuttings [7, p. 55761]. Instead, EPA defined a stylized calculation that provided a fast path to the aquifer underlying the Yucca Mountain repository. The limit on the dose, unconditioned by the probability of the event, was 15 mrem/yr (0.15 mSv/yr) in the first $10^4$ yr and 100 mrem/yr (1 mSv/yr) beyond $10^4$ yr (Table A-1)

## A.2 Undisturbed Performance

A PA involves consideration of both undisturbed and disturbed FEPs that are formed into scenarios to model the evolution of the repository. The undisturbed scenarios involve consideration of the gradual degradation of the condition of the engineered components to the point at which water can eventually breach the disposal packages and come into contact with waste, leading to mobilization and transport of radionuclides in groundwater.

### A.2.1 Generic Disposal System Demonstration

The UFD Campaign is developing the capability to model different disposal environments and waste form options [12]. Because the model effort is only beginning, any current results cannot be construed as the performance of a disposal system, but the results demonstrate the current capabilities of the individual generic disposal system (GDS) models, and give an indication of the type of comparative analysis that can be conducted for various components of the disposal system in the future. Here, we present results from the crystalline, deep borehole, clay/shale, and salt demonstrations which confirm results from the international community and which will be repeated in future GDS analysis.

### A.2.2 Generic Crystalline Repository Dose

Figure A-1 shows mean annual dose to an individual at an assumed 5-km accessible environment boundary for the undisturbed scenario, from radionuclides released by diffusion through a bentonite buffer around breached packages in a generic crystalline repository. The radionuclide $^{129}$I is the dominant contributor to mean annual dose within a few thousand years and dominates to the end of the $10^6$-yr period.

The breached packages hold either 10 PWR assemblies or 5 defense HLW canisters. The fractures intersecting packages with PWR assemblies flow with mean discharge of $4.5 \times 10^{-4}$ $m^3$/yr, while fractures intersecting packages with defense HLW flow with a mean discharge of $1.4 \times 10^{-4}$ $m^3$/yr. Degradation of the waste package was not modeled in the generic studies. Rather, the number of breached waste packages was varied between 0.1% and 1% of the total number of waste packages. The small fraction of breached packages was based on detailed analyses from the Swedish Nuclear Fuel and Waste Management Company (SKB) program.

In sensitivity/uncertainty analysis, the crystalline bedrock porosity was the most important parameter (natural barrier parameter) in explaining the variation of $^{129}$I dose about the mean throughout the $10^6$-yr period. Also, the defense HLW glass degradation rate was important at the earlier times, while the commercial SNF degradation rate was important at the end of the simulation. Parameters with similar influence include the mean travel time of water in the far field at early times and the $^{129}$I sorption coefficient for the bentonite buffer towards the end of the simulation [12, §3.2.3.2.2].

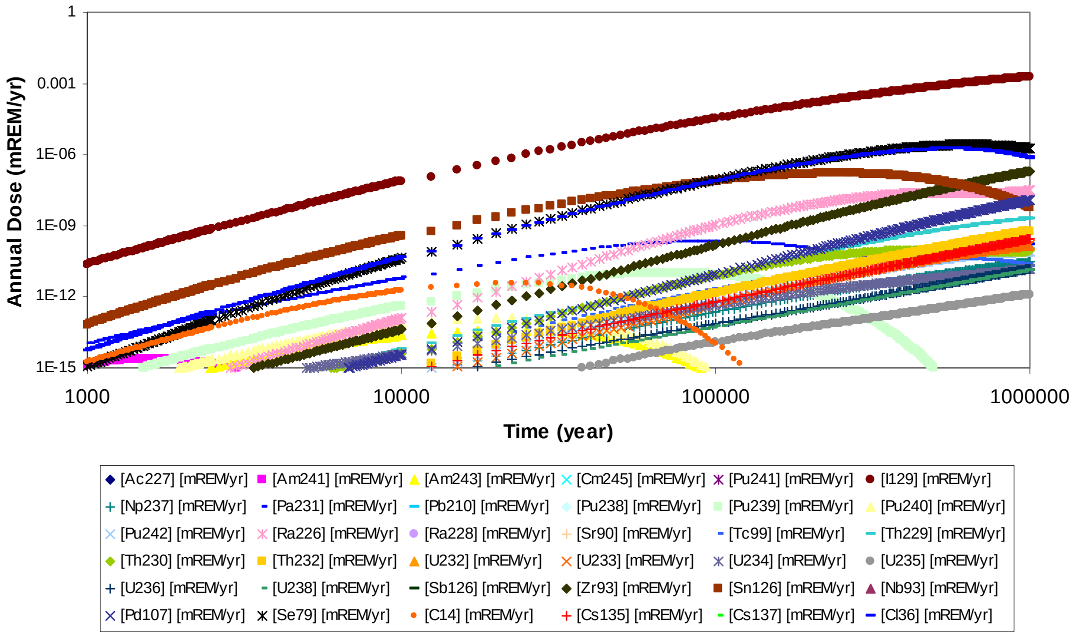
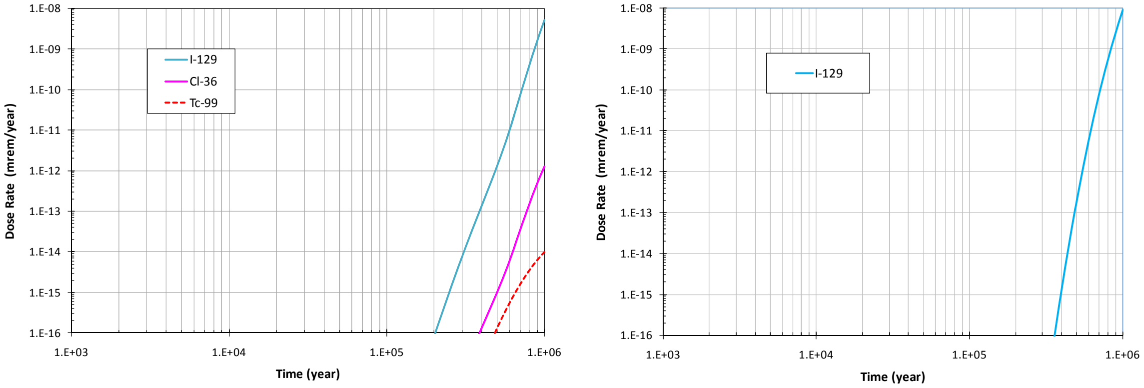


**Figure A-1. Contribution of radionuclides to mean annual dose for crystalline repository for undisturbed scenario [12, Figure 3.2-6].**

## A.2.3 Generic Deep Borehole Repository Doses

The deep borehole disposal concept consists of drilling deep boreholes into crystalline rocks for permanent disposal of high level radioactive waste. The repository design consisted of drilling boreholes to a depth of 5 km, emplacing packages in the lower 2 km, and constructing 1-km seals above the waste. The upper 2 km of the deep borehole are plugged and backfilled. The case with 400 packages of commercial SNF stacked on top of each other, each containing a single PWR assembly, is shown in Figure A-2a. The radionuclide $^{129}$I is the dominant dose contributor, but the calculated mean doses are negligibly small.

Figure A-2b shows the results of a defense HLW inventory for a base permeability case. The upward volumetric water flow rate is different for HLW than for commercial SNF inventory because of the different decay heat. The $^{129}$I is the only dose-contributing radionuclide at the accessible environment, and the calculated mean dose is negligibly small.



(a) Commercial SNF (b) Defense HLW

**Figure A-2. Mean annual dose at the accessible environment located above the deep borehole repository (a) Commercial SNF; (b) Defense HLW [12, Figure 3.4-9].**

## A.2.4 Generic Clay/Shale Repository Doses

For the generic clay/shale disposal system, the radionuclides that contribute to the mean total annual dose are shown in Figure A-3, with $^{129}$I, $^{36}$Cl, and $^{135}$Cs fission products dominating the dose (expressed as mrem per metric ton) for $10^7$ yr.

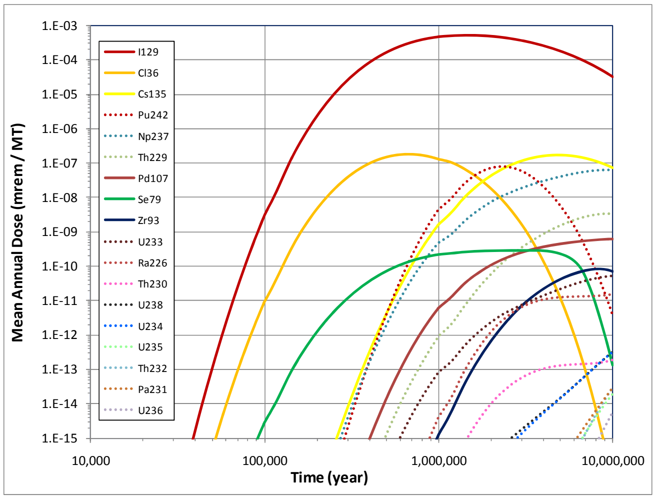


**Figure A-3. Radionuclide contribution to the mean total annual dose, clay GDS model – "baseline" parameter set [12, Figure 3.3-27].**

## A.2.5 Yucca Mountain Undisturbed Case

For the undisturbed performance in the oxygenated environment of the proposed Yucca Mountain disposal system, $^{99}$Tc and $^{129}$I were the most important radionuclides in the first $10^4$ years because packages containing HLW failed first, but remained important for the full $10^6$ year period of performance. Only after $10^4$ years did $^{237}$Np (an actinide) and colloidal $^{239}$Pu and $^{240}$Pu become more important [21].

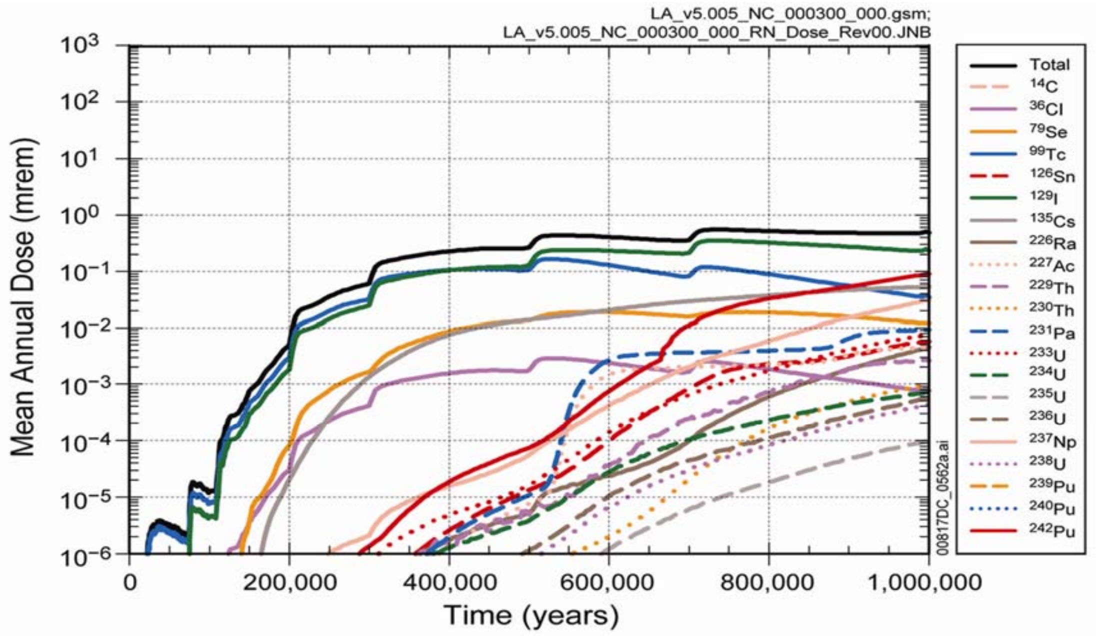


**Figure A-4. Radionuclides contributing to mean annual dose for the nominal scenario class ([13, Figure 8.2-2[a]]**

## A.3 Human Intrusion Disturbance

In the more recent EPA standard, 40 CFR 197, for the Yucca Mountain disposal system, doses from human intrusion that results in a fast path through the EBS and a portion of the NBS are calculated. The remaining portion of the natural barrier can still noticeably reduce actinide transport as noted in the following generic repositories.

### A.3.1 Human Intrusion into a Generic Salt Repository

For the case of inadvertent human intrusion into generic salt repository with features similar to those of WIPP, dissolved radionuclides are transported upward by pressurized brine from an underlying pressurized brine reservoir through the intrusion borehole and are released directly to the overlying aquifer. The aquifer water flow rate is several orders of magnitude greater than the brine flow rate in the interbeds of the host salt. The model assumes that the location of the borehole penetration in the repository is uncertain and the model does not consider the distance from the penetration location to the repository boundary.

The calculated mean annual doses at the assumed 5-km accessible environment boundary, from intrusion into a package containing 10 assemblies of commercial PWR SNF, are shown in Figure A-5 [12, §3.1.4.2]. The dominant mean annual dose contributor is $^{14}$C for about first $3\times10^3$ yr; $^{237}$Np is the dominant mean annual dose contributor from about $3\times10^3$ yr to about $3.5\times10^4$ yr and again from about $2\times10^5$ yr to the end of analysis ($10^6$ yr); and $^{239}$Pu is the dominant mean dose contributor from about $3.5\times10^4$ yr to about $2\times10^5$ yr. Although actinide removal might seemingly be beneficial for a salt repository, the mean peak dose of 0.1 mrem/yr at $10^5$ yr is so far below the 100 mrem/yr limit that reducing the dose or its uncertainty would not be warranted.

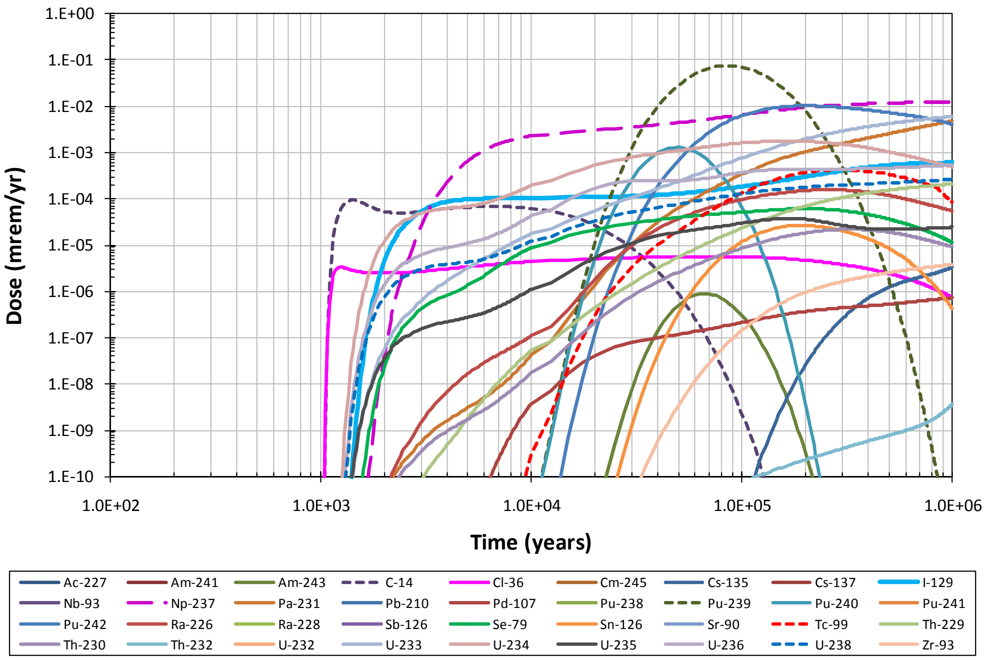


**Figure A-5. Mean annual dose at 5-km accessible environment for generic salt repository after inadvertent human intrusion into a package containing 10 assemblies of commercial PWR SNF [12, Figure 3.1-15].**

## A.3.2 Human Intrusion into a Generic Crystalline Repository

Figure A-6 shows the mean annual dose at the assumed 5-km accessible environment boundary after inadvertent human intrusion into a generic crystalline disposal system for commercial SNF. The $^{129}$I mean annual dose surpasses $^{241}$Am, $^{243}$Am, $^{239}$Pu and $^{240}$Pu after only a few thousand years, and is the dominant contributor at the end of the $10^6$-yr period. The second largest contributor to total dose is $^{226}$Ra. The long half-life, high solubility, and weak sorption of $^{129}$I contribute to its higher mean dose. The mean peak dose, $10^{-3}$ mrem/yr, is 4.5 orders of magnitude below the 15 mrem/yr limit in the first $10^4$ yr and 5 orders of magnitude below the 100 mrem/yr limit after $10^4$ yr, from intrusion into a package containing 10 assemblies of commercial PWR SNF [12].

In a sensitivity/uncertainty analysis, the uncertainty in the mean travel time of water in the far-field, crystalline bedrock porosity, and the commercial SNF waste form degradation rate were the most important parameters in explaining the variation about the mean in the contribution of $^{129}$I in the first $10^4$ yr. The influence of mean travel time and bedrock porosity decreases thereafter (natural barrier parameters), and the influence of the commercial SNF waste form degradation rate (EBS parameter) increases thereafter [12, p. 64]

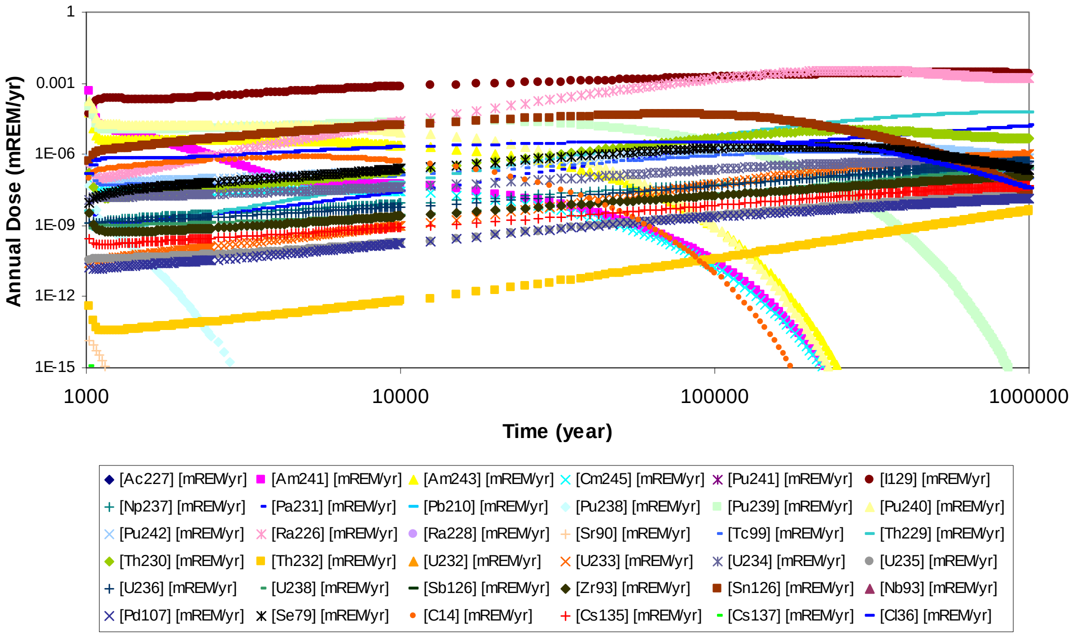


**Figure A-6. Mean annual dose for generic crystalline repository after human intrusion into a package containing 10 assemblies of commercial PWR SNF [12, Figure 3.2-5].**

### A.3.3 Human Intrusion into Proposed Yucca Mountain Repository

For TSPA-LA, the maximum of the mean annual dose occurs within a few thousand years after the intrusion at 200,000 yr into packages containing either 21 PWR assemblies, 44 BWR assemblies, or 4 HLW canisters and 1 DOE-owned spent nuclear fuel (DSNF) assembly (Figure A-7). The maximum values of the mean and median are less than 0.013 mrem/yr and 0.011 mrem/yr, respectively, well below the regulatory limit of 100 mrem/yr. Following the intrusion, the long-lived fission products that are highly soluble and non-sorbing, such as $^{99}$Tc and $^{129}$I, dominate the annual dose for about 50,000 years after the intrusion while the waste form is degrading [15, Fig. 8.1-17[a]].

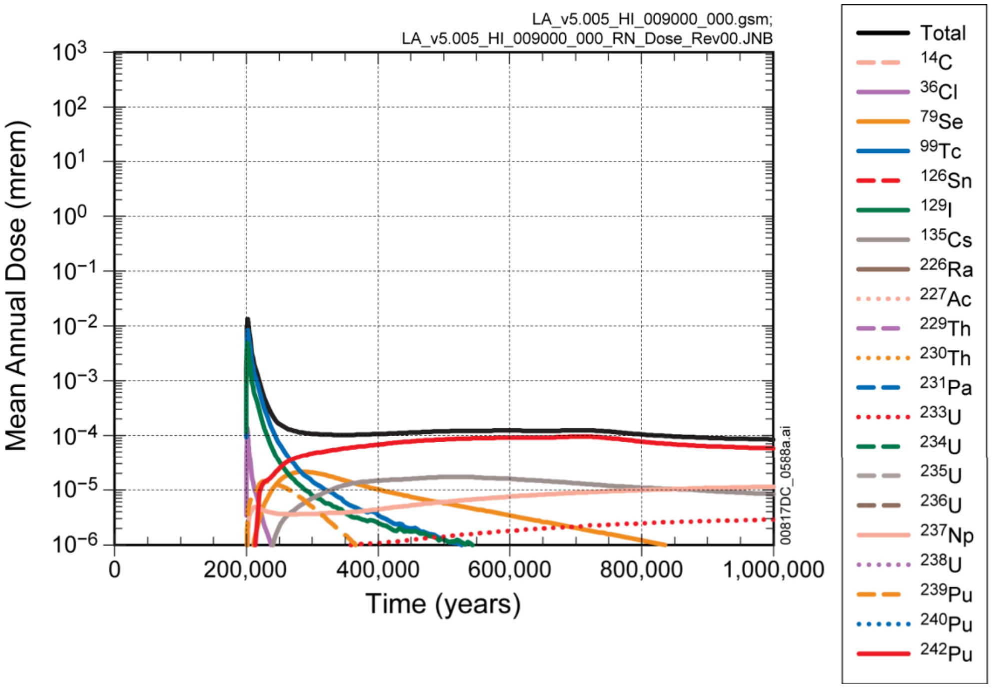


**Figure A-7. Contribution of individual radionuclides to mean annual dose in TSPA-LA for intrusion into a package containing 21 PWR assemblies, 44 BWR assemblies, or 4 HLW canisters and 1 DSNF assembly [15, Fig. 8.1-17[a]]**

## A.4 Dose after Natural Disturbance of Proposed Yucca Mountain Repository

For TSPA-LA, the maximum dose of 2 mrem/yr (0.02 mSv/yr) occurred at $10^6$ yr from the contribution of both the seismic scenario dose (Figure A-8) and the igneous dike intrusion dose (Figure A-9) [15, Figs. 8.2-12[a] & 8.2-8[a]]. The EBS design had evolved by TSPA-LA such that releases from disruptive events were the dominate release mechanism for most of the $10^6$ yr regulatory period, rather than corrosion and degradation in the undisturbed scenario class. The fission products $^{99}$Tc and $^{129}$I were the most important for the seismic ground motion subclass and prior to $10^4$ yr for the igneous intrusion scenario subclass. The important radionuclides at $10^6$ yr for the igneous intrusion scenario subclass were $^{242}$Pu, $^{237}$Np, $^{226}$Ra, and $^{129}$I.

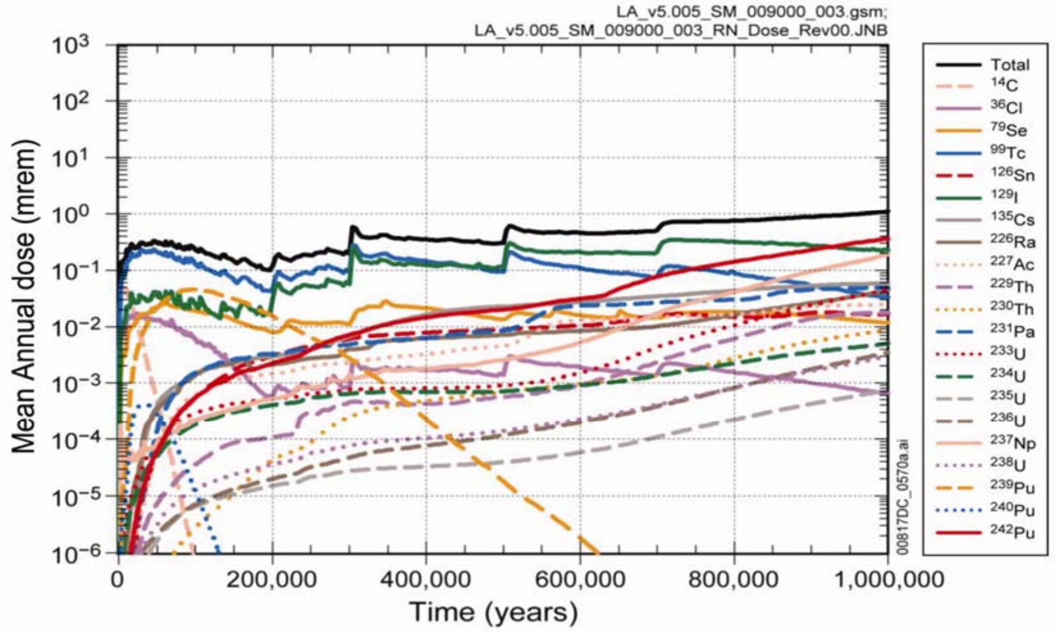


**Figure A-8. Contribution of individual radionuclides to mean annual dose for the seismic ground motion subclass for TSPA-LA [15, Fig. 8.2-12[a]].**

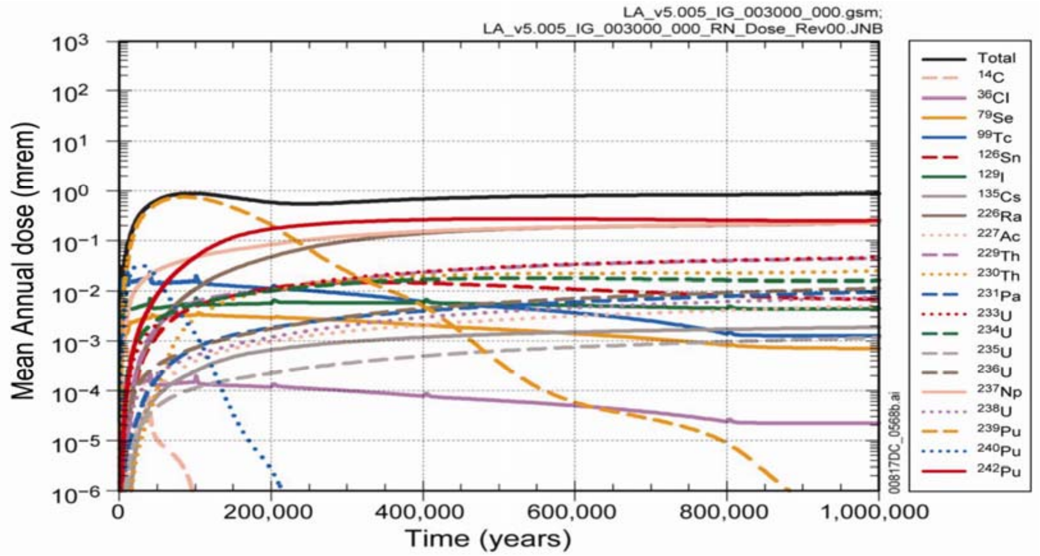


**Figure A-9. Contribution of individual radionuclides to expected mean annual dose for igneous intrusion disruption for TSPA-LA [15, Fig. 8.2-8[a]].**

# APPENDIX B: PAST UNCERTAINTY ANALYSIS OF PROPOSED YUCCA MOUNTAIN DISPOSAL SYSTEM

Only a real disposal system has uncertainty. Although one may want to evaluate a generic disposal system assuming different states of knowledge to understand its behavior, the state of knowledge is not uncertain; rather, it is defined. In generic studies, parameter importance might be evaluated to illustrate behavior about the system, but then the parameter distribution can only be constrained by what is physically possible, not by the uncertainty measured at an actual site. In concept, a similar situation occurs related to model uncertainty and scenario uncertainty for generic repositories.

In the sensitivity/uncertainty analyses conducted for the proposed Yucca Mountain disposal system, parameters of the natural barrier system are often important, as shown by how often natural barrier parameters are mentioned in Table B-1, far right column) (e.g., percolation in the unsaturated zone and fluid flux in the saturated zone were always important in explaining the variability of the results about the mean dose. As corrosion resistance of the waste package was increased, a few parameters related to the package robustness become the most important (parameters also unrelated to the fuel cycle). Uncertainty in natural parameters, such as colloid concentration and biological dose conversion factors (BDCFs) for $^{99}$Tc and $^{237}$Np and uncertainty of parameters in the waste form such as the solubility of U and Pu, were important but at the end of the list. Furthermore, this behavior was observed at Yucca Mountain in several iterations of the PAs.

## B.1 TSPA-VA Results

In the total system performance assessment conducted for the viability assessment in 1998 (TSPA-VA) [47], the uncertainty in the fraction of packages with drips ($f^{WPdrip}$) was the most important parameter in both the $10^4$ and $10^6$ yr periods in explaining the variation in dose (Table B-1). In an earlier analysis conducted in 1993 (TSPA-93) [48], the fraction of waste contacted by seepage and the fraction of packages with rubble had been important and were related to $f^{WPdrip}$ in concept. In the first $10^4$-yr period, the next two important parameters were also related to the package: general corrosion rate of Alloy 22 under drips ( $\dot{s}_{A22}^{wet}$ ), and fraction of packages that failed early at 1000 yr ( $F_{CSNF,SE,drip}^{early}$ ). Diffusive transport through initial pin-holes dominated releases when the package first breached. Hence, as the protective function and modeling sophistication of slow enlargement of perforations on the package improved, the importance of waste form degradation decreased. Over the entire simulation period, two additional parameters were important: the uncertainty in the dilution factor in the saturated zone (SZ) ($f^{dilute}$), which had been added to account for transverse dispersion in the 1-D SZ transport, and the uncertainty in dose conversion factors ( $f_r^{BDCF}$ ), whose uncertainty was included for the first time.

## B.2 TSPA-SR Results

For the analysis of the undisturbed scenario conducted for the site recommendation (TSPA-SR), the most important parameters prior to $10^5$ yr were associated with package degradation (Table B-1) [49, Fig. 5.1-4]. After $10^5$ yr, SZ and unsaturated zone (UZ) flow parameters (calibrated hydrologic parameters for infiltration/percolation of the UZ, $h$, and the groundwater flux in the SZ, $q_{ff}^{SZ}$ ) became more important after sufficient packages had degraded [49, Fig. 5.1-11]. The $h$ is the infiltration-hydrologic calibration index and related to the uncertainty in percolation. For igneous eruptive releases, the important uncertain parameters at $10^4$ yr were the rate of igneous intrusion into the repository ($\lambda_V$), time of igneous intrusion into the repository ($\tau_V$), and wind speed ($v^{wind}$) [49, Fig. 5.1-20]. For igneous groundwater release at $10^4$

yr, the rate of intrusion into the repository ($\lambda_V$) was most important followed by the UZ infiltration-hydrologic property set and SZ Darcy flow ($h$ and $q^{SZ}_{ff}$) [49, Fig. 5.1-21].

## B.3 TSPA-LA Results

Similar to TSPA-VA and TSPA-SR, the uncertainty in parameters related to the package contributed to the uncertainty in the dose results throughout the $10^6$-yr regulatory period for the analysis conducted for the TSPA-LA [13]. Specifically, (1) the fraction of yield stress ($f^{SCCthres}_{SG}$) to calculate the residual stress threshold (i.e., $\sigma^{SCCthres}_{SG} = f^{SCC}_{SG}\sigma^{yield}$) for initiating stress corrosion cracking (SCC) on smooth surfaces from seismic ground motion, and (2) the temperature dependence on the Alloy 22 corrosion rate ($\kappa^{GC}_1$) which had been reintroduced from TSPA-VA, are important (Table B-1). Understandably, the uncertainty in rate of igneous intrusion into the repository ($\lambda_V$) was still important. The next most important parameters were those related to flow in the UZ and SZ ($h$ and $q^{SZ}_{ff}$, respectively).

Although not nearly as significant, some parameters related to the inventory were important: the dose conversion factors ($f^{BDCF}_{Tc99}(arid)$) and $f^{BDCF}_{Np237}(arid)$; uncertainty in the solubility of uranium and plutonium ($S_U$ and $S_{Pu}$) and colloid concentration in groundwater ($C^{coll}_{gw}$), which was associated with colloid-facilitated actinide transport.

**Table B-1. Uncertain parameters influencing spread in dose in major PAs for Yucca Mountain.**

| TSPA | Scenario | Period | Uncertain Parameter | System |
|---|---|---|---|---|
| VA | Undisturb | $10^4$ | Fraction of packages with seepage ($f^{WPdrip}$) | Natural |
| | | | General corrosion rate of Alloy 22 layer of package under drips ($\dot{s}^{GC}_{A22,wet}$) | Package |
| | | | Fraction of CSNF packages failed early at 1000 yr under drips ($F^{early}_{CSNF}$) | Package |
| | | | Factor to approximate transverse dispersion in 1-D transport ($f^{dilute}$) | Natural |
| | | $10^6$ | Fraction of packages with seepage ($f^{WPdrip}$) | Natural |
| | | | Factor to approximate transverse dispersion in 1-D transport ($f^{dilute}$) | Natural |
| | | | Biological dose conversion factor for all radionuclides ($f^{BDCF}_r$) | Natural |
| | | | General corrosion rate of Alloy 22 layer of package under drips ($\dot{s}^{GC}_{A22,wet}$) | Package |
| SR | Undisturb | $10^5$ | Stress corrosion cracking (SCC) stress profile for outer lid of package ($\sigma^{hoop}_{outerweld}$) | Package |
| | | | General corrosion rate of Alloy 22 for outer lid of package ($\dot{s}^{GC}_{A22,outlid}$) | Package |
| | | | General corrosion rate of Alloy 22 for inner lid of package ($\dot{s}^{GC}_{A22,inlid}$) | Package |
| | | | Single-porosity, flowing-fracture Darcy velocity in saturated zone ($q^{SZ}_{ff}$) | Natural |
| | | | SCC stress profile for outer lid of package ($\sigma^{hoop}_{outerweld}$) | Package |
| | | $10^6$ | Infiltration-hydrologic calibration property set for unsaturated zone ($h$) | Natural |
| | | | $Q^{farm}$ (uncertainty in water usage per farm) | Natural |
| | | | Single-porosity, flowing-fracture Darcy velocity in saturated zone ($q^{SZ}_{ff}$) | Natural |
| | Igneous Eruption | $10^4$ | Rate of igneous intrusion of dike into repository ($\lambda_V$) | Natural |
| | | | Time of igneous dike intrusion ($\tau_V$) | Natural |
| | | | Wind speed during eruption ($v^{wind}$) | Natural |

| TSPA | Scenario | Period | Uncertain Parameter | System |
|---|---|---|---|---|
| | Igneous GW | $10^6$ | Rate of igneous intrusion of dike into repository ($\lambda_V$) | Natural |
| | | | Single-porosity, flowing-fracture Darcy velocity in saturated zone ( $q_{ff}^{SZ}$ ) | Natural |
| | | | Infiltration-hydrologic calibration property set for unsaturated zone ($h$ ) | Natural |
| LA | All Scenarios | $10^4$ | Fraction of yield threshold for initiation of SCC from seismic damage where $\sigma_{SG}^{SCCthres} = f_{SG}^{SCCthres}\sigma^{yield}$ | Package |
| | | | Rate of igneous intrusion of dike into repository ($\lambda_V$) | Natural |
| | | | Single-porosity, flowing-fracture Darcy velocity in saturated zone ( $q_{ff}^{SZ}$ ) | Natural |
| | | | Infiltration-hydrologic calibration property set for unsaturated zone ($h$ ) (1st 3000 yr) | Natural |
| | | | Biologic dose conversion factor for $^{99}$Tc for current modern interglacial climate ( $f_{Tc99}^{BCDF}$ ) | Natural |
| | | $5\times10^5$ | Rate of igneous intrusion of dike into repository ($\lambda_V$) | Natural |
| | | | Temperature dependence coefficient of Alloy 22 corrosion rate ( $\kappa_1^{GC}$ ) | Package |
| | | | Single-porosity, flowing-fracture Darcy velocity in saturated zone ( $q_{ff}^{SZ}$ ) | Natural |
| | | | Uncertainty in uranium solubility for low ionic strength solution $S_U$ ) | Waste |
| | | | Biologic dose conversion factor for $^{237}$Np for current modern interglacial climate ( $f_{Np237}^{BDCF}$ ) | Natural |
| | | | Fraction of yield threshold for initiation of SCC from seismic damage ( $f_{SG}^{SCCthres}$ ) | Package |
| | | | Colloid concentration in groundwater ( $C_{gw}^{coll}$ ) | Natural |
| | | | Uncertainty Pu solubility in low ionic strength solution ( $S_{Pu}$ ) | Waste |
| | | | Spacing between flowing fractures in saturated zone ( $2B_{ff}^{SZ} + 2b_{ff}^{SZ}$ ) (1st 3000 yr) | Natural |
| | Igneous GW | $10^4$ | Rate of igneous intrusion of dike into repository ($\lambda_V$) | Natural |
| | | | Single-porosity, flowing-fracture Darcy velocity in saturated zone ( $q_{ff}^{SZ}$ ) | Natural |
| | | | Biologic dose conversion factor for $^{99}$Tc for current modern interglacial climate ( $f_{Tc99}^{BCDF}$ ) | Natural |
| | | | Infiltration-hydrologic calibration property set for unsaturated zone ($h$ ) | Natural |
| | | $5\times10^5$ | Rate of igneous intrusion of dike into repository ($\lambda_V$) | Natural |
| | | | Single-porosity, flowing-fracture Darcy velocity in saturated zone ( $q_{ff}^{SZ}$ ) | Natural |
| | | | Infiltration-hydrologic calibration property set for unsaturated zone ($h$ ) | Natural |
| | | | Spacing between flowing fractures in saturated zone ( $2B_{ff}^{SZ} + 2b_{ff}^{SZ}$ ) | Natural |
| | | | Uncertainty Pu solubility in low ionic strength solution ( $S_{Pu}$ ) | Waste |
| | | | Biologic dose conversion factor for $^{237}$Np for current modern interglacial climate ( $f_{Np237}^{BDCF}$ ) | Natural |
| | Undisturb | $10^4$ | Fraction of yield threshold for initiation of SCC from seismic damage ( $f_{SG}^{SCCthres}$ ) | Package |
| | | | Biologic dose conversion factor for $^{99}$Tc for current modern interglacial climate ( $f_{Tc99}^{BCDF}$ ) | Natural |
| | | $5\times10^5$ | Temperature dependent coefficient of Alloy 22 corrosion rate ( $\kappa_1^{GC}$ ) | Package |
| | | | Fraction of yield threshold for initiation of SCC from seismic damage ( $f_{SG}^{SCCthres}$ ) | Package |

## B.4 Uncertainty in EBS FEPs Affected by Alternative Fuel Cycles

Another example of uncertainty inputs to PA can be drawn from the Swedish repository investigations. A variety of data were used in the illustration of uncertainty due to lack of knowledge and spatial variability. In the Swedish case, in which a pin-hole failure occurs in a waste package, which, in turn, leads to fuel dissolution and transport to the far-field, the key uncertainties relating to the EBS are:

- the number of failed canisters
- the canister defect size
- fuel dissolution rate
- concentration (solubility) limits
- buffer porosities, diffusivities, and sorption coefficients
- backfill diffusivity and sorption coefficients

Of these, only the fuel dissolution rate, solubility limits and the sorption coefficients are impacted by the fuel cycle, with dissolution rate being a function of the waste form and the sorption coefficients being a function of waste content. Clearly, with an advanced fuel cycle, the uncertainty in actinide sorption coefficients would be removed, but the uncertainty associated with sorption of fission product radionuclides would remain.

# APPENDIX C: List of Features, Events, and Processes for Used Fuel Disposition Campaign

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 0.0.00.00 | 0. ASSESSMENT BASIS | | |
| 0.1.02.01 | Timescales of Concern | | 0.1.02.00.0A |
| 0.1.03.01 | Spatial Domain of Concern | Size and geometry of host rock, surrounding units of geosphere, and biosphere | 0.1.03.00.0A |
| 0.1.09.01 | Regulatory Requirements and Exclusions | | 0.1.09.00.0A |
| 0.1.10.01 | Model Issues | - Conceptual model<br>- Mathematical implementation<br>- Geometry and dimensionality<br>- Process coupling<br>- Boundary and initial conditions | 0.1.10.00.0A |
| 0.1.10.02 | Data Issues | - Parameterization and values<br>- Correlations<br>- Uncertainty | 0.1.10.00.0A |
| 1.0.00.00 | 1. EXTERNAL FACTORS | | |
| 1.1.00.00 | 1. REPOSITORY ISSUES | | |
| 1.1.01.01 | Open Boreholes | - Site investigation boreholes (open, improperly sealed)<br>- Preclosure and postclosure monitoring boreholes<br>- Enhanced flow pathways from EBS | 1.1.01.01.0A<br>1.1.11.00.0A |
| 1.1.02.01 | Chemical Effects from Preclosure Operations<br>- In EBS<br>- In EDZ<br>- In Host Rock | - Water contaminants (explosives residue, diesel, organics, etc.)<br>- Water chemistry different than host rock (e.g., oxidizing)<br>- Undesirable materials left<br>- Accidents and unplanned events | 1.1.02.00.0A<br>1.1.02.03.0A<br>1.1.12.01.0A<br>2.2.01.01.0B |
| 1.1.02.02 | Mechanical Effects from Preclosure Operations<br>- In EBS<br>- In EDZ<br>- In Host Rock | - Creation of excavation-disturbed zone (EDZ)<br>- Stress relief<br>- Boring and blasting effects<br>- Rock reinforcement effects (drillholes)<br>- Accidents and unplanned events<br>- Enhanced flow pathways<br>[See also Evolution of EDZ in 2.2.01.01] | 1.1.01.01.0B<br>1.1.02.00.0B<br>1.1.12.01.0A<br>2.2.01.01.0A |
| 1.1.02.03 | Thermal-Hydrologic Effects from Preclosure Operations<br>- In EBS<br>- In EDZ<br>- In Host Rock | - Site flooding<br>- Preclosure ventilation<br>- Accidents and unplanned events | 1.1.02.01.0A<br>1.1.02.02.0A<br>1.1.12.01.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 1.1.08.01 | Deviations from Design and Inadequate Quality Control | - Error in waste emplacement (waste forms, waste packages, waste package support materials)<br>- Error in EBS component emplacement (backfill, seals, liner)<br>- Inadequate excavation / construction (planning, schedule, implementation)<br>- Aborted / incomplete closure of repository<br>- Material and/or component defects | 1.1.03.01.0A1<br>.1.03.01.0B<br>1.1.04.01.0A<br>1.1.07.00.0A<br>1.1.08.00.0A<br>1.1.09.00.0A |
| 1.1.10.01 | Control of Repository Site | - Active controls (controlled area)<br>- Retention of records<br>- Passive controls (markers) | 1.1.05.00.0A<br>1.1.10.00.0A |
| 1.1.13.01 | Retrievability | | 1.1.13.00.0A |
| 1.2.00.00 | 2. GEOLOGICAL PROCESSES AND EFFECTS | | |
| 1.2.01.00 | 2.01. LONG-TERM PROCESSES | | |
| 1.2.01.01 | Tectonic Activity – Large Scale | - Uplift<br>- Folding | 1.2.01.01.0A |
| 1.2.02.01 | Subsidence | | 2.2.06.04.0A |
| 1.2.05.01 | Metamorphism | - Structural changes due to natural heating and/or pressure | 1.2.05.00.0A |
| 1.2.08.01 | Diagenesis | - Mineral alteration due to natural processes | 1.2.08.00.0A |
| 1.2.09.01 | Diapirism | - Plastic flow of rocks under lithostatic loading<br>- Salt / evaporates<br>- Clay | 1.2.09.00.0A<br>1.2.09.01.0A |
| 1.2.10.01 | Large-Scale Dissolution | | 1.2.09.02.0A |
| 1.2.03.00 | 2.03.SEISMIC ACTIVITY | | |
| 1.2.03.01 | Seismic activity impacts EBS and/or EBS components | - Mechanical damage to EBS (from ground motion, rockfall, drift collapse, fault displacement)<br>[See also Mechanical Impacts in 2.1.07.04, 2.1.07.05, 2.1.07.06, 2.1.07.07, 2.1.07.08, and 2.1.07.10] | 1.2.02.03.0A<br>1.2.03.02.0A<br>1.2.03.02.0B<br>1.2.03.02.0C |
| 1.2.03.02 | Seismic activity impacts geosphere | - Future faults alter flow pathways and change hydraulic parameters | |
| 1.2.04.00 | 2.04. IGNEOUS ACTIVITY | | |
| 1.2.04.01 | Igneous activity impacts EBS and/or EBS components | - Mechanical damage to EBS (from igneous intrusion)<br>- Chemical interaction with magmatic volatiles<br>- Transport of radionuclides (in magma, pyroclasts, vents)<br>[See also Mechanical Impacts in 2.1.07.04, 2.1.07.05, 2.1.07.06, 2.1.07.07, and 2.1.07.08] | 1.2.04.03.0A<br>1.2.04.04.0A<br>1.2.04.04.0B<br>1.2.04.05.0A<br>1.2.04.06.0A |
| 1.2.04.01 | Geothermal regime | - Present and future geothermal regime | |
| 1.3.00.00 | 3. CLIMATIC PROCESSES AND EFFECTS | | |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 1.3.01.01 | Climate Change<br>- Natural | - Variations in precipitation and temperature<br>- Long-term global<br>- Short-term regional and local<br>[See also Human Influences on Climate in 1.4.01.01]<br>[contributes to Precipitation in 2.3.08.01, Surface Runoff and Evapotranspiration in 2.3.08.02] | 1.3.01.00.0A |
| 1.3.04.01 | Periglacial Effects | - Permafrost<br>- Seasonal freeze/thaw | 1.3.04.00.0A |
| 1.3.05.01 | Glacial and Ice Sheet Effects | - Glaciation<br>- Isostatic depression<br>- Future stress regime<br>- Melt water | 1.3.05.00.0A |
| 1.4.00.00 | 4. FUTURE HUMAN ACTIONS | | |
| 1.4.01.01 | Human Influences on Climate<br>- Intentional | - Variations in precipitation and temperature<br>- Global, regional, and/or local<br>- Greenhouse gases, ozone layer failure<br>[See also Climate Change in 1.3.01.01] | 1.4.01.00.0A<br>1.4.01.01.0A<br>1.4.01.02.0A1<br>.4.01.04.0A |
| 1.4.02.01 | Human Influences on Climate<br>- Accidental | - Variations in precipitation and temperature<br>- Global, regional, and/or local<br>- Greenhouse gases, ozone layer failure<br>[See also Climate Change in 1.3.01.01] | 1.4.01.00.0A<br>1.4.01.01.0A<br>1.4.01.02.0A1<br>.4.01.04.0A |
| 1.4.03.01 | Human Intrusion<br>- Deliberate | - Drilling (resource exploration, …)<br>- Mining / tunneling<br>- Unintrusive site investigation (airborne, surface-based, …)<br>[See also Control of Repository Site in 1.1.10.01] | 1.4.02.01.0A<br>1.4.02.02.0A<br>1.4.03.00.0A<br>1.4.04.00.0A<br>1.4.04.01.0A<br>1.4.05.00.0A<br>3.3.06.01.0A |
| 1.4.04.01 | Human Intrusion<br>- Inadvertent | - Drilling (resource exploration, …)<br>- Mining / tunneling<br>- Unintrusive site investigation (airborne, surface-based, …)<br>[See also Control of Repository Site in 1.1.10.01] | 1.4.02.01.0A<br>1.4.02.02.0A<br>1.4.03.00.0A<br>1.4.04.00.0A<br>1.4.04.01.0A<br>1.4.05.00.0A<br>3.3.06.01.0A |
| 1.4.11.01 | Explosions and Crashes from Human Activities | - War<br>- Sabotage<br>- Testing<br>- Resource exploration / exploitation<br>- Aircraft | 1.4.11.00.0A |
| 1.5.00.00 | 5. OTHER | | |
| 1.5.01.01 | Meteorite Impact | - Cratering, host rock removal<br>- Exhumation of waste<br>- Alteration of flow pathways | 1.5.01.01.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 1.5.01.02 | Extraterrestrial Events | - Solar systems (supernova)<br>- Celestial activity (sun - solar flares, gamma-ray bursters; moon – earth tides)<br>- Alien life forms | 1.5.01.02.0A<br>1.5.03.02.0A |
| 1.5.03.01 | Earth Planetary Changes | - Changes in earth's magnetic field<br>- Changes in earth's gravitational field (tides) | 1.5.03.01.0A<br>1.5.03.02.0A |
| 2.0.00.00 | 2. DISPOSAL SYSTEM FACTORS | | |
| 2.1.00.00 | 1. WASTES AND ENGINEERED FEATURES | | |
| 2.1.01.00 | 1.01. INVENTORY | | |
| 2.1.01.01 | Waste Inventory<br>- Radionuclides<br>- Non-Radionuclides | - Composition<br>- Enrichment / Burn-up | 2.1.01.01.0A |
| 2.1.01.02 | Radioactive Decay and Ingrowth | | 3.1.01.01.0A |
| 2.1.01.03 | Heterogeneity of Waste Inventory<br>- Waste Package Scale<br>- Repository Scale | - Composition<br>- Enrichment / Burn-up<br>- Damaged Area | 2.1.01.03.0A<br>2.1.01.04.0A |
| 2.1.01.04 | Interactions Between Co-Located Waste | | 2.1.01.02.0A<br>2.1.01.02.0B |
| 2.1.02.00 | 1.02. WASTE FORM | | |
| 2.1.02.01 | CSNF (Commercial SNF) Degradation<br>- Alteration / Phase Separation<br>- Dissolution / Leaching<br>- Radionuclide Release | Degradation is dependent on:<br>- Composition<br>- Geometry / Structure<br>- Enrichment / Burn-up<br>- Surface Area<br>- Gap and Grain Fraction<br>- Damaged Area<br>- THC Conditions<br>[See also Mechanical Impact in 2.1.07.06 and Thermal-Mechanical Effects in 2.1.11.06] | 2.1.02.02.0A<br>2.1.02.01.0A<br>2.1.02.28.0A<br>2.1.02.07.0A |
| 2.1.02.06 | CSNF Cladding Degradation and Failure | - Initial damage<br>- General Corrosion<br>- Microbially Influenced Corrosion<br>- Localized Corrosion<br>- Enhanced Corrosion (silica, fluoride)<br>- Stress Corrosion Cracking<br>- Hydride Cracking<br>- Unzipping<br>- Creep<br>- Internal Pressure<br>- Mechanical Impact | 2.1.02.11.0A<br>2.1.02.12.0A<br>2.1.02.13.0A<br>2.1.02.14.0A<br>2.1.02.15.0A<br>2.1.02.16.0A<br>2.1.02.17.0A<br>2.1.02.18.0A<br>2.1.02.27.0A<br>2.1.02.21.0A<br>2.1.02.22.0A<br>2.1.02.23.0A<br>2.1.02.25.0A<br>2.1.02.25.0B<br>2.1.02.19.0A<br>2.1.02.26.0A<br>2.1.02.20.0A<br>2.1.02.24.0A<br>2.1.09.03.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.02.01 | DSNF (DOE-owned SNF) Degradation<br>- Alteration / Phase Separation<br>- Dissolution / Leaching<br>- Radionuclide Release | Degradation is dependent on:<br>- Composition<br>- Geometry / Structure<br>- Enrichment / Burn-up<br>- Surface Area<br>- Gap and Grain Fraction<br>- Damaged Area<br>- THC Conditions<br><br>[See also Mechanical Impact in 2.1.07.06 and Thermal-Mechanical Effects in 2.1.11.06] | 2.1.02.02.0A<br>2.1.02.01.0A<br>2.1.02.28.0A<br>2.1.02.07.0A |
| 2.1.02.06 | DSNF Cladding Degradation and Failure | - Initial damage<br>- General Corrosion<br>- Microbially Influenced Corrosion<br>- Localized Corrosion<br>- Enhanced Corrosion (silica, fluoride)<br>- Stress Corrosion Cracking<br>- Hydride Cracking<br>- Unzipping<br>- Creep<br>- Internal Pressure<br>- Mechanical Impact | 2.1.02.11.0A<br>2.1.02.12.0A<br>2.1.02.13.0A<br>2.1.02.14.0A<br>2.1.02.15.0A<br>2.1.02.16.0A<br>2.1.02.17.0A<br>2.1.02.18.0A<br>2.1.02.27.0A<br>2.1.02.21.0A<br>2.1.02.22.0A<br>2.1.02.23.0A<br>2.1.02.25.0A<br>2.1.02.25.0B<br>2.1.02.19.0A<br>2.1.02.26.0A<br>2.1.02.20.0A<br>2.1.02.24.0A<br>2.1.09.03.0A |
| 2.1.02.01 | NSNF (Navall SNF) Degradation<br>- Alteration / Phase Separation<br>- Dissolution / Leaching<br>- Radionuclide Release | Degradation is dependent on:<br>- Composition<br>- Geometry / Structure<br>- Enrichment / Burn-up<br>- Surface Area<br>- Gap and Grain Fraction<br>- Damaged Area<br>- THC Conditions<br><br>[See also Mechanical Impact in 2.1.07.06 and Thermal-Mechanical Effects in 2.1.11.06] | 2.1.02.02.0A<br>2.1.02.01.0A<br>2.1.02.28.0A<br>2.1.02.07.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.02.06 | NSNF Cladding Degradation and Failure | - Initial damage<br>- General Corrosion<br>- Microbially Influenced Corrosion<br>- Localized Corrosion<br>- Enhanced Corrosion (silica, fluoride)<br>- Stress Corrosion Cracking<br>- Hydride Cracking<br>- Unzipping<br>- Creep<br>- Internal Pressure<br>- Mechanical Impact | 2.1.02.11.0A<br>2.1.02.12.0A<br>2.1.02.13.0A<br>2.1.02.14.0A<br>2.1.02.15.0A<br>2.1.02.16.0A<br>2.1.02.17.0A<br>2.1.02.18.0A<br>2.1.02.27.0A<br>2.1.02.21.0A<br>2.1.02.22.0A<br>2.1.02.23.0A<br>2.1.02.25.0A<br>2.1.02.25.0B<br>2.1.02.19.0A<br>2.1.02.26.0A<br>2.1.02.20.0A<br>2.1.02.24.0A<br>2.1.09.03.0A |
| 2.1.02.02 | HLW (Glass, Ceramic, Metal) Degradation<br>- Alteration / Phase Separation<br>- Dissolution / Leaching<br>- Cracking<br>- Radionuclide Release | Degradation is dependent on:<br>- Composition<br>- Geometry / Structure<br>- Surface Area<br>- Damaged / Cracked Area<br>- Mechanical Impact<br>- THC Conditions<br><br>[See also Mechanical Impact in 2.1.07.07 and Thermal-Mechanical Effects in 2.1.11.06] | 2.1.02.03.0A<br>2.1.02.05.0A |
| 2.1.02.04 | HLW (Glass, Ceramic, Metal) Recrystallization | | 2.1.02.06.0A |
| 2.1.02.03 | Degradation of Organic/Cellulosic Materials in Waste | [See also Complexation in EBS in 2.1.09.54] | 2.1.02.10.0A |
| 2.1.02.05 | Pyrophoricity or Flammable Gas from SNF or HLW | [See also Gas Explosions in EBS in 2.1.12.04] | 2.1.02.08.0A<br>2.1.02.29.0A |
| 2.1.03.00 | 1.03. WASTE CONTAINER | | |
| 2.1.03.01 | Early Failure of Waste Packages | - Manufacturing defects<br>- Improper sealing<br><br>[See also Deviations from Design in 1.1.08.01] | 2.1.03.08.0A |
| 2.1.03.02 | General Corrosion of Waste Packages | - Dry-air oxidation<br>- Humid-air corrosion<br>- Aqueous phase corrosion<br>- Passive film formation and stability | 2.1.03.01.0A |
| 2.1.03.03 | Stress Corrosion Cracking (SCC) of Waste Packages | - Crack initiation, growth and propagation<br>- Stress distribution around cracks | 2.1.03.02.0A |
| 2.1.03.04 | Localized Corrosion of Waste Packages | - Pitting<br>- Crevice corrosion<br>- Salt deliquescence<br><br>[See also 2.1.09.06 Chemical Interaction with Backfill] | 2.1.03.03.0A<br>2.1.09.28.0A |
| 2.1.03.05 | Hydride Cracking of Waste Packages | - Hydrogen diffusion through metal matrix<br>- Crack initiation and growth in metal hydride phases | 2.1.03.04.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.03.06 | Microbially Influenced Corrosion (MIC) of Waste Packages | | 2.1.03.05.0A |
| 2.1.03.07 | Internal Corrosion of Waste Packages Prior to Breach | | 2.1.03.06.0A |
| 2.1.03.08 | Evolution of Flow Pathways in Waste Packages | - Evolution of physical form of waste package<br>- Plugging of cracks in waste packages<br>[See also Evolution of Flow Pathways in EBS in 2.1.08.06, Mechanical Impacts in 2.1.07.05, 2.1.07.06, and 2.1.07.07, Thermal-Mechanical Effects in 2.1.11.06 and 2.1.11.07] | 2.1.03.10.0A<br>2.1.03.11.0A |
| 2.1.04.00 | 1.04. BUFFER / BACKFILL | | |
| 2.1.04.01 | Evolution of Backfill | - Alteration<br>- Thermal expansion / Degradation<br>- Swelling / Compaction<br>- Erosion / Dissolution<br>- Evolution of backfill flow pathways<br>[See also Evolution of Flow Pathways in EBS in 2.1.08.06, Mechanical Impact in 2.1.07.04, Thermal-Mechanical Effects in 2.1.11.08, Chemical Interaction in 2.1.09.06] | 2.1.04.05.0A<br>2.1.04.03.0A |
| 2.1.05.00 | 1.05. SEALS | | |
| 2.1.05.01 | Evolution of Seals | - Alteration / Degradation / Cracking<br>- Erosion / Dissolution<br>[See also Mechanical Impact in 2.1.07.08, Thermal-Mechanical Effects in 2.1.11.09, Chemical Interaction in 2.1.09.08] | 2.1.05.03.0A |
| 2.1.06.00 | 1.06. OTHER EBS MATERIALS | | |
| 2.1.06.01 | Degradation of Liner / Rock Reinforcement Materials in EBS | - Alteration / Degradation / Cracking<br>- Corrosion<br>- Erosion / Dissolution / Spalling<br>[See also Mechanical Impact in 2.1.07.08, Thermal-Mechanical Effects in 2.1.11.09, Chemical Interaction in 2.1.09.07] | 2.1.06.02.0A |
| 2.1.07.00 | 1.07. MECHANICAL PROCESSES | | |
| 2.1.07.01 | Rockfall | - Dynamic loading (block size and velocity)<br>[See also Mechanical Effects on Host Rock in 2.2.07.01] | 2.1.07.01.0A |
| 2.1.07.02 | Drift Collapse | - Static loading (rubble volume)<br>- Alteration of seepage<br>- Alteration of EBS flow pathways<br>- Alteration of EBS thermal environment<br>[See also Evolution of Flow Pathways in EBS in 2.1.08.06, Chemical Effects of Drift Collapse in 2.1.09.12, and Effects of Drift Collapse on TH in 2.1.11.04, Mechanical Effects on Host Rock in 2.2.07.01] | 2.1.07.02.0A<br>1.2.03.02.0D |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.07.03 | Mechanical Effects of Backfill | - Protection of other EBS components from rockfall / drift collapse | 2.1.04.04.0A |
| 2.1.07.04 | Mechanical Impact on Backfill | - Rockfall / Drift collapse<br>- Hydrostatic pressure<br>- Internal gas pressure<br><br>[See also Degradation of Backfill in 2.1.04.01 and Thermal-Mechanical Effects in 2.1.11.08] | 2.1.04.05.0A |
| 2.1.07.05 | Mechanical Impact on Waste Packages | - Rockfall / Drift collapse<br>- Waste package movement<br>- Hydrostatic pressure<br>- Internal gas pressure<br>- Swelling corrosion products<br><br>[See also Thermal-Mechanical Effects in 2.1.11.07] | 2.1.03.07.0A<br>2.1.07.04.0A<br>2.1.09.03.0B |
| 2.1.07.06 | Mechanical Impact on SNF Waste Form | - Drift collapse<br>- Swelling corrosion products<br><br>[see also Thermal-Mechanical Effects in 2.1.11.06] | 2.1.07.02.0A<br>2.1.09.03.0B |
| 2.1.07.07 | Mechanical Impact on HLW Waste Form | - Drift collapse<br>- Swelling corrosion products<br><br>[See also Thermal-Mechanical Effects in 2.1.11.06] | 2.1.07.02.0A<br>2.1.09.03.0B |
| 2.1.07.08 | Mechanical Impact on Other EBS Components<br>- Seals<br>- Liner/Rock Reinforcement Materials<br>- Waste Package Support Materials | - Rockfall / Drift collapse<br>- Movement<br>- Hydrostatic pressure<br>- Swelling corrosion products<br><br>[See also Thermal-Mechanical Effects in 2.1.11.09] | 2.1.07.02.0A<br>2.1.09.03.0C |
| 2.1.07.09 | Mechanical Effects at EBS Component Interfaces | - Component-to-component contact (static or dynamic) | 2.1.06.07.0B<br>2.1.08.15.0A |
| 2.1.07.10 | Mechanical Degradation of EBS | - Floor buckling<br>- Fault displacement<br>- Initial damage from excavation / construction<br>- Consolidation of EBS components<br>- Degradation of waste package support structure<br>- Alteration of EBS flow pathways<br><br>[See also Mechanical Effects from Preclosure in 1.1.02.02, Evolution of Flow Pathways in EBS in 2.1.08.06, Drift Collapse in 2.1.07.02, Degradation in 2.1.04.01, 2.1.05.01, and 2.1.06.01, and Mechanical Effects on Host Rock in 2.2.07.01] | 2.1.06.05.0B<br>2.1.07.06.0A<br>1.2.02.03.0A<br>2.1.08.15.0A |
| 2.1.08.00 | 1.08. HYDROLOGIC PROCESSES | | |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.08.01 | Flow Through the EBS | - Saturated / Unsaturated flow<br>- Preferential flow pathways<br>- Density effects on flow<br>- Initial hydrologic conditions<br>- Flow pathways out of EBS<br>- Hydraulic properties<br>[See also Open Boreholes in 1.1.01.01, Thermal-Hydrologic Effects from Preclosure in 1.1.02.03, Flow in Waste Packages in 2.1.08.02, Flow in Backfill in 2.1.08.03, Flow through Seals 2.1.08.04, Flow through Liner in 2.1.08.05, Thermal Effects on Flow in 2.1.11.10, Effects of Gas on Flow in 2.1.12.02] | 2.1.08.09.0A<br>2.1.08.07.0A<br>2.1.08.05.0A |
| 2.1.08.02 | Flow In and Through Waste Packages | - Saturated / Unsaturated flow<br>- Movement as thin films or droplets | 2.1.03.10.0A<br>2.1.03.11.0A |
| 2.1.08.03 | Flow in Backfill | - Fracture / Matrix flow | 2.1.04.01.0A |
| 2.1.08.04 | Flow Through Seals | | 2.1.05.01.0A |
| 2.1.08.05 | Flow Through Liner / Rock Reinforcement Materials in EBS | | 2.1.06.04.0A |
| 2.1.08.06 | Alteration and Evolution of EBS Flow Pathways | - Drift collapse<br>- Degradation/consolidation of EBS components<br>- Plugging of flow pathways<br>- Formation of corrosion products<br>- Water ponding<br>[See also Evolution of Flow Pathways in WPs in 2.1.03.08, Evolution of Backfill in 2.1.04.01, Drift Collapse in 2.1.07.02, and Mechanical Degradation of EBS in 2.1.07.10] | 2.1.08.12.0A<br>2.1.08.15.0A<br>2.1.03.10.0A<br>2.1.03.11.0A<br>2.1.09.02.0A |
| 2.1.08.07 | Condensation Forms in Repository<br>- On Drift Roof / Walls<br>- On EBS Components | - Heat transfer (spatial and temporal distribution of temperature and relative humidity)<br>- Dripping<br>[See also Heat Generation in EBS in 2.1.11.01, Effects on EBS Thermal Environment in 2.1.11.03 and 2.1.11.04] | 2.1.08.04.0A<br>2.1.08.04.0B |
| 2.1.08.08 | Capillary Effects in EBS | - Wicking | 2.1.08.06.0A |
| 2.1.08.09 | Influx/Seepage Into the EBS | - Water influx rate (spatial and temporal distribution)<br>[see also Open Boreholes in 1.1.01.01, Thermal Effects on Flow in EBS in 2.1.11.10, Flow Through Host Rock in 2.2.08.01, Effects of Excavation on Flow in 2.2.08.04] | 2.1.08.01.0A |
| 2.1.09.00 | 1.09. CHEMICAL PROCESSES - CHEMISTRY | | |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.09.01 | Chemistry of Water Flowing into the Repository | - Chemistry of influent water (spatial and temporal distribution)<br>[See also Chemistry in Host Rock 2.2.09.01] | 2.2.08.12.0A<br>2.1.08.01.0A |
| 2.1.09.02 | Chemical Characteristics of Water in Waste Packages | - Water composition (radionuclides, dissolved species, …)<br>- Initial void chemistry (air / gas)<br>- Water chemistry (pH, ionic strength, $pCO_2$)<br>- Reduction-oxidation potential<br>- Reaction kinetics<br>- Influent chemistry (from tunnels and/or backfill)<br>[See also Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]<br>- Evolution of water chemistry / interaction with waste packages | 2.1.09.01.0B<br>2.1.02.09.0A<br>2.2.08.12.0B<br>2.1.09.06.0A<br>2.1.09.07.0A |
| 2.1.09.03 | Chemical Characteristics of Water in Backfill | - Water composition (radionuclides, dissolved species, …)<br>- Water chemistry (pH, ionic strength, $pCO_2$)<br>- Reduction-oxidation potential<br>- Reaction kinetics<br>- Influent chemistry (from tunnels and/or waste package)<br>[See also Chemistry in Waste Packages in 2.1.09.02, Chemistry in Tunnels in 2.1.09.04]<br>- Evolution of water chemistry / interaction with backfill | 2.1.04.02.0A<br>2.1.09.01.0A<br>2.1.09.06.0B<br>2.1.09.07.0B |
| 2.1.09.04 | Chemical Characteristics of Water in Drifts | - Water composition (radionuclides, dissolved species, …)<br>- Water chemistry (pH, ionic strength, $pCO_2$)<br>- Reduction-oxidation potential<br>- Reaction kinetics<br>- Influent chemistry (from near-field host rock)<br>- Initial chemistry (from construction / emplacement)<br>[See also Chemical Effects from Preclosure in 1.1.02.01, Chemistry of Water Flowing in 2.1.09.01, Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03]<br>- Evolution of water chemistry / interaction with seals, liner/rock reinforcement materials, waste package support materials | 2.1.09.01.0A<br>2.1.09.06.0B<br>2.1.09.07.0B |
| 2.1.09.05 | Chemical Interaction of Water with Corrosion Products<br>- In Waste Packages<br>- In Backfill<br>- In Drifts | - Corrosion product formation and composition (waste form, waste package internals, waste package)<br>- Evolution of water chemistry in waste packages, in backfill, and in tunnels<br>[Contributes to Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04] | 2.1.09.02.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.09.06 | Chemical Interaction of Water with Backfill<br>- On Waste Packages<br>- In Backfill<br>- In Drifts | - Backfill composition and evolution (bentonite, crushed rock, ...)<br>- Evolution of water chemistry in backfill, and in tunnels<br>- Enhanced degradation of waste packages (crevice formation)<br><br>[Contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04, Localized Corrosion of WPs in 2.1.03.04] | 2.1.04.02.0A |
| 2.1.09.07 | Chemical Interaction of Water with Liner / Rock Reinforcement and Cementitious Materials in EBS<br>- In Backfill<br>- In Drifts | - Liner composition and evolution (concrete, metal, ...)<br>- Rock reinforcement material composition and evolution (grout, rock bolts, mesh, ...)<br>- Other cementitious materials composition and evolution<br>- Evolution of water chemistry in backfill, and in tunnels<br><br>[Contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04] | 2.1.06.01.0A |
| 2.1.09.08 | Chemical Interaction of Water with Other EBS Components<br>- In Waste Packages<br>- In Drifts | - Seals composition and evolution<br>- Waste Package Support composition and evolution (concrete, metal, ...)<br>- Other EBS components (other metals (copper), ...)<br>- Evolution of water chemistry in backfill, and in tunnels<br><br>[Contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04] | 2.1.06.05.0D<br>2.1.03.09.0A |
| 2.1.09.09 | Chemical Effects at EBS Component Interfaces | - Component-to-component contact (chemical reactions)<br>- Consolidation of EBS components | 2.1.06.07.0A<br>2.1.08.15.0A |
| 2.1.09.10 | Chemical Effects of Waste-Rock Contact | - Waste-to-host rock contact (chemical reactions)<br>- Component-to-host rock contact (chemical reactions) | 2.1.09.11.0A<br>2.2.01.02.0B |
| 2.1.09.11 | Electrochemical Effects in EBS | - Enhanced metal corrosion | 2.1.09.09.0A<br>2.1.09.27.0A |
| 2.1.09.12 | Chemical Effects of Drift Collapse | - Evolution of water chemistry in backfill and in drifts (from altered seepage, from altered thermal-hydrology)<br><br>[Contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04] | 1.2.03.02.0E |
| 2.1.09.13 | Radionuclide Speciation and Solubility in EBS<br>- In Waste Form<br>- In Waste Package<br>- In Backfill<br>- In Drift | - Dissolved concentration limits<br>- Limited dissolution due to inclusion in secondary phase<br>- Enhanced dissolution due to alpha recoil<br><br>[Controlled by Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04] | 2.1.09.04.0A<br>2.1.09.10.0A<br>2.1.02.04.0A |
| 2.1.09.50 | 1.09. CHEMICAL PROCESSES - TRANSPORT | | |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.09.51 | Advection of Dissolved Radionuclides in EBS<br>- In Waste Form<br>- In Waste Package<br>- In Backfill<br>- In Drift | - Flow pathways and velocity<br>- Advective properties (porosity, tortuosity)<br>- Dispersion<br>- Saturation<br>[See also Gas Phase Transport in 2.1.12.03] | 2.1.09.08.0B<br>2.1.04.09.0A<br>2.1.09.27.0A |
| 2.1.09.52 | Diffusion of Dissolved Radionuclides in EBS<br>- In Waste Form<br>- In Waste Package<br>- In Backfill<br>- In Drift | - Gradients (concentration, chemical potential)<br>- Diffusive properties (diffusion coefficients)<br>- Flow pathways and velocity<br>- Saturation | 2.1.09.08.0A<br>2.1.04.09.0A<br>2.1.09.27.0A |
| 2.1.09.53 | Sorption of Dissolved Radionuclides in EBS<br>- In Waste Form<br>- In Waste Package<br>- In Backfill<br>- In Drift | - Surface complexation properties<br>- Mineral surface areas<br>- Ion exchange<br>- Flow pathways and velocity<br>- Saturation<br>[See also Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04] | 2.1.09.05.0A<br>2.1.04.09.0A<br>2.1.09.27.0A |
| 2.1.09.54 | Complexation in EBS | - Formation of organic complexants (humates, fulvates, organic waste)<br>- Enhanced transport of radionuclides associated with organic complexants<br>[See also Degradation of Organics in Waste in 2.1.02.03] | 2.1.09.13.0A |
| 2.1.09.55 | Formation of Colloids in EBS<br>- In Waste Form<br>- In Waste Package<br>- In Backfill<br>- In Drift | - Formation of intrinsic colloids<br>- Formation of pseudo colloids (host rock fragments, waste form fragments, corrosion products, microbes)<br>- Formation of co-precipitated colloids<br>- Sorption/attachment of radionuclides to colloids (clay, silica, waste form, FeOx, microbes) | 2.1.09.15.0A<br>2.1.09.16.0A<br>2.1.09.17.0A<br>2.1.09.18.0A<br>2.1.09.25.0A |
| 2.1.09.56 | Stability of Colloids in EBS<br>- In Waste Form<br>- In Waste Package<br>- In Backfill<br>- In Drift | - Chemical stability of attachment (dependent on water chemistry)<br>- Mechanical stability of colloid (dependent on colloid size, gravitational settling) | 2.1.09.23.0A<br>2.1.09.26.0A<br>2.1.09.21.0A |
| 2.1.09.57 | Advection of Colloids in EBS<br>- In Waste Form<br>- In Waste Package<br>- In Backfill<br>- In Drift | - Flow pathways and velocity<br>- Advective properties (porosity, tortuosity)<br>- Dispersion<br>- Saturation<br>- Colloid concentration | 2.1.09.19.0B<br>2.1.04.09.0A |
| 2.1.09.58 | Diffusion of Colloids in EBS<br>- In Waste Form<br>- In Waste Package<br>- In Backfill<br>- In Drift | - Gradients (concentration, chemical potential)<br>- Diffusive properties (diffusion coefficients)<br>- Flow pathways and velocity<br>- Saturation<br>- Colloid concentration | 2.1.09.24.0A<br>2.1.04.09.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.09.59 | Sorption of Colloids in EBS<br>- In Waste Form<br>- In Waste Package<br>- In Backfill<br>- In Tunnel | - Surface complexation properties<br>- Flow pathways and velocity<br>- Saturation<br>- Colloid concentration<br><br>[See also Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04] | 2.1.09.19.0A<br>2.1.04.09.0A |
| 2.1.09.60 | Sorption of Colloids at Air-Water Interface in EBS | | 2.1.09.22.0A |
| 2.1.09.61 | Filtration of Colloids in EBS | - Physical filtration (dependent on flow pathways, colloid size)- Electrostatic filtration | 2.1.09.20.0A2<br>.1.09.21.0A |
| 2.1.09.62 | Radionuclide Transport Through Liners and Seals | - Advection<br>- Dispersion<br>- Diffusion<br>- Sorption<br><br>[Contributes to Radionuclide release from EBS in 2.1.09.63] | 2.1.05.02.0A |
| 2.1.09.63 | Radionuclide Release from the EBS<br>- Dissolved<br>- Colloidal<br>- Gas Phase | - Spatial and temporal distribution of releases to the host rock (due to varying flow pathways and velocities, varying component degradation rates, varying transport properties)<br><br>[Contributions from Dissolved in 2.1.09.51/52/53, Colloidal in 2.1.09.57/58/59, Gas Phase in 2.1.12.03, Liners and Seals in 2.1.09.62] | 2.2.07.06.0A<br>2.2.07.06.0B |
| 2.1.10.00 | 1.10. BIOLOGICAL PROCESSES | | |
| 2.1.10.01 | Microbial Activity in EBS<br>- Natural<br>- Anthropogenic | - Effects on corrosion<br>- Formation of complexants<br>- Formation of microbial colloids<br>- Formation of biofilms<br>- Biodegradation<br>- Biomass production<br>- Bioaccumulation<br><br>[See also Microbiallly Influenced Corrosion in 2.1.03.06, Complexation in EBS in 2.1.09.54, Radiological Mutation of Microbes in 2.1.13.03] | 2.1.10.01.0A |
| 2.1.11.00 | 1.11. THERMAL PROCESSES | | |
| 2.1.11.01 | Heat Generation in EBS | - Heat transfer (spatial and temporal distribution of temperature and relative humidity)<br><br>[See also Thermal-Hydrologic Effects from Preclosure in 1.1.02.03, Waste Inventory in 2.1.01.01] | 2.1.11.01.0A<br>2.1.11.02.0A |
| 2.1.11.02 | Exothermic Reactions in EBS | - Oxidation of SNF<br>- Hydration of concrete | 2.1.11.03.0A |
| 2.1.11.03 | Effects of Backfill on EBS Thermal Environment | - Thermal blanket<br>- Condensation<br>- Thermal properties | 2.1.04.04.0A |
| 2.1.11.04 | Effects of Drift Collapse on EBS Thermal Environment | - Thermal blanket<br>- Condensation | 1.2.03.02.0D |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.11.05 | Effects of Influx (Seepage) on Thermal Environment | - Temperature and relative humidity (spatial and temporal distribution)<br>[See also Influx/Seepage into EBS in 2.1.08.09] | 2.1.08.01.0B<br>2.1.08.01.0A |
| 2.1.11.06 | Thermal-Mechanical Effects on Waste Form and In-Package EBS Components | - Alteration<br>- Cracking<br>- Thermal expansion / stress | 2.1.11.05.0A |
| 2.1.11.07 | Thermal-Mechanical Effects on Waste Packages | - Thermal sensitization / phase changes<br>- Cracking<br>- Thermal expansion / stress / creep | 2.1.07.05.0A<br>2.1.11.06.0A<br>2.1.11.07.0A |
| 2.1.11.08 | Thermal-Mechanical Effects on Backfill | - Alteration<br>- Cracking<br>- Thermal expansion / stress | 2.1.11.07.0A<br>2.1.04.04.0A |
| 2.1.11.09 | Thermal-Mechanical Effects on Other EBS Components<br>- Seals<br>- Liner / Rock Reinforcement Materials<br>- Waste Package Support Structure | - Alteration<br>- Cracking<br>- Thermal expansion / stress<br>- Thermal properties | 2.1.11.07.0A |
| 2.1.11.10 | Thermal Effects on Flow in EBS | - Altered influx/seepage<br>- Altered saturation / relative humidity (dry-out, resaturation)<br>- Condensation | 2.1.08.03.0A<br>2.1.08.11.0A<br>2.1.11.09.0A |
| 2.1.11.11 | Thermally-Driven Flow (Convection) in EBS | - Convection | 2.1.11.09.0B<br>2.1.11.09.0C |
| 2.1.11.12 | Thermally-Driven Buoyant Flow / Heat Pipes in EBS | - Vapor flow | 2.2.10.10.0A |
| 2.1.11.13 | Thermal Effects on Chemistry and Microbial Activity in EBS | | 2.1.11.08.0A |
| 2.1.11.14 | Thermal Effects on Transport in EBS | - Thermal diffusion (Soret effect)<br>- Thermal osmosis | 2.1.11.10.0A |
| 2.1.12.00 | 1.12. GAS SOURCES AND EFFECTS | | |
| 2.1.12.01 | Gas Generation in EBS | - Repository Pressurization<br>- Mechanical Damage to EBS Components<br>- He generation from waste from alpha decay<br>- $H_2$ generation from waste package corrosion<br>- $CO_2$, $CH_4$, and $H_2S$ generation from microbial degradation | 2.1.12.01.0A<br>2.1.12.02.0A<br>2.1.12.03.0A<br>2.1.12.04.0A |
| 2.1.12.02 | Effects of Gas on Flow Through the EBS | - Two-phase flow<br>- Gas bubbles<br>[See also Buoyant Flow/Heat Pipes in 2.1.11.12] | 2.1.12.06.0A<br>2.1.12.07.0A |
| 2.1.12.03 | Gas Transport in EBS | - Gas phase transport<br>- Gas phase release from EBS | 2.1.12.07.0A<br>2.1.12.06.0A<br>2.2.10.10.0A |
| 2.1.12.04 | Gas Explosions in EBS | [See also Flammable Gas from Waste in 2.1.02.05] | 2.1.12.08.0A |
| 2.1.13.00 | 1.13. RADIATION EFFECTS | | |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.1.13.01 | Radiolysis<br>- In Waste Package<br>- In Backfill<br>- In Drift | - Gas generation<br>- Altered water chemistry | 2.1.13.01.0A |
| 2.1.13.02 | Radiation Damage to EBS Components<br>- Waste Form<br>- Waste Package<br>- Backfill<br>- Other EBS Components | - Enhanced waste form degradation<br>- Enhanced waste package degradation<br>- Enhanced backfill degradation<br>- Enhanced degradation of other EBS components (liner/rock reinforcement materials, seals, waste support structure) | 2.1.13.02.0A |
| 2.1.13.03 | Radiological Mutation of Microbes | | 2.1.13.03.0A |
| 2.1.14.00 | 1.14. NUCLEAR CRITICALITY | | |
| 2.1.14.01 | Criticality In-Package | - Formation of critical configuration | 2.1.14.15.0A<br>2.1.14.16.0A<br>2.1.14.21.0A<br>2.1.14.22.0A |
| 2.1.14.02 | Criticality in EBS or Near-Field | - Formation of critical configuration | 2.1.14.17.0A<br>2.1.14.23.0A |
| 2.2.00.00 | 2. GEOLOGICAL ENVIRONMENT | | |
| 2.2.01.00 | 2.01. EXCAVATION DISTURBED ZONE (EDZ) | | |
| 2.2.01.01 | Evolution of EDZ | - Size and extent,<br>- Structure and heterogeneities<br>- Geomechanical properties<br>- Hydraulic properties<br>- Flow pathways<br>- Chemical characteristics of groundwater in EDZ<br>- Radionuclide speciation and solubility in EDZ<br>- Thermal-mechanical effects<br>- Thermal-chemical alteration<br>- Thermal-hydrologic-mechanical effects<br>- Oxidation of the host rock<br>- Geomechanical stability<br><br>[See also Mechanical Effects of Excavation in 1.1.02.02] | 2.2.01.04.0A |
| 2.2.02.00 | 2.02. HOST ROCK | | |
| 2.2.02.01 | Stratigraphy and Properties of Host Rock | - Rock units<br>- Thickness, lateral extent, heterogeneities, discontinuities, contacts<br>- Geomechanical properties<br>- Flow pathways<br><br>[See also Fractures in 2.2.05.01 and Faults in 2.2.05.02] | 2.2.03.01.0A<br>2.2.03.02.0A |
| 2.2.03.00 | 2.03. OTHER GEOLOGIC UNITS | | |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.2.03.01 | Stratigraphy and Properties of Other Geologic Units (Non-Host-Rock)<br>- Confining units<br>- Aquifers | - Rock units<br>- Thickness, lateral extent, heterogeneities, discontinuities, contacts<br>- Physical properties<br>- Flow pathways<br>[See also Fractures in 2.2.05.01 and Faults in 2.2.05.02] | 2.2.03.01.0A<br>2.2.03.02.0A |
| 2.2.05.00 | 2.05. FLOW AND TRANSPORT PATHWAYS | | |
| 2.2.05.01 | Fractures<br>- Host Rock | - Flow and transport properties<br>[See also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01] | 1.2.02.01.0A<br>2.2.07.13.0A |
| 2.2.05.02 | Fractures<br>- Other Geologic Units | - Flow and transport properties<br>[See also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01] | 1.2.02.01.0A<br>2.2.07.13.0A |
| 2.2.05.03 | Faults<br>- Host Rock | - Flow and transport properties<br>[See also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01] | 1.2.02.02.0A<br>2.2.07.13.0A |
| 2.2.05.04 | Faults<br>- Other Geologic Units | - Flow and transport properties<br>[See also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01] | 1.2.02.02.0A<br>2.2.07.13.0A |
| 2.2.05.05 | Alteration and Evolution of Geosphere Flow Pathways<br>- Host Rock<br>- Other Geologic Units | - Changes In rock properties<br>- Changes in faults<br>- Changes in fractures<br>- Plugging of flow pathways<br>- Changes in saturation<br>[See also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01, Fractures in 2.2.05.01, and Faults in 2.2.05.02]<br>[See also Thermal-Mechanical Effects in 2.2.11.06 and Thermal-Chemical Alteration in 2.2.11.07] | 2.2.12.00.0A<br>2.2.12.00.0B |
| 2.2.07.00 | 2.07. MECHANICAL PROCESSES | | |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.2.07.01 | Mechanical Effects on Host Rock | - From subsidence<br>- From salt creep<br>- From clay deformation<br>- From granite deformation (rockfall / drift collapse into tunnels)<br>- Chemical precipitation / dissolution<br><br>[See also Subsidence in 1.2.02.01, Thermal-Mechanical Effects in 2.2.11.06 and Thermal-Chemical Alteration in 2.2.11.07] | 2.2.06.04.0A<br>2.2.06.05.0A |
| 2.2.07.02 | Mechanical Effects on Other Geologic Units | - From subsidence<br>- Chemical precipitation / dissolution<br><br>[See also Subsidence in 1.2.02.01, Thermal-Mechanical Effects in 2.2.11.06 and Thermal-Chemical Alteration in 2.2.11.07] | 2.2.06.04.0A |
| 2.2.07.03 | Stress regime | - | |
| 2.2.08.00 | 2.08. HYDROLOGIC PROCESSES | | |
| 2.2.08.01 | Flow Through the Host Rock | - Saturated flow<br>- Fracture flow / matrix imbibition<br>- Unsaturated flow (fingering, capillarity, episodicity, perched water)<br>- Preferential flow pathways<br>- Density effects on flow<br>- Flow pathways out of Host Rock<br>- Paleo-hydrogeology<br><br>[See also Influx/Seepage into EBS in 2.1.08.09, Alteration of Flow Pathways in 2.2.05.03, Thermal Effects on Flow in 2.2.11.01, Effects of Gas on Flow in 2.2.12.02] | 2.2.07.02.0A<br>2.2.07.03.0A<br>2.2.07.04.0A<br>2.2.07.05.0A<br>2.2.07.07.0A<br>2.2.07.08.0A<br>2.2.07.09.0A<br>2.2.07.12.0A |
| 2.2.08.02 | Flow Through the Other Geologic Units<br>- Confining units<br>- Aquifers | - Saturated flow<br>- Fracture flow / matrix imbibition<br>- Unsaturated flow (fingering, capillarity, episodicity, perched water)<br>- Preferential flow pathways<br>- Density effects on flow<br>- Flow pathways out of Other Geologic Units<br>- Paleo-hydrogeology<br><br>[See also Alteration of Flow Pathways in 2.2.05.03, Thermal Effects on Flow in 2.2.11.01, Effects of Gas on Flow in 2.2.12.02] | 2.2.07.02.0A<br>2.2.07.03.0A<br>2.2.07.04.0A<br>2.2.07.05.0A<br>2.2.07.07.0A<br>2.2.07.08.0A<br>2.2.07.09.0A<br>2.2.07.12.0A |
| 2.2.08.03 | Effects of Recharge on Geosphere Flow<br>- Host Rock<br>- Other Geologic Units | - Infiltration rate<br>- Water table rise/decline<br><br>[See also Infiltration in 2.3.08.03 | 1.3.07.01.0A<br>1.3.07.02.0A<br>1.3.07.02.0B |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.2.08.04 | Effects of Repository Excavation on Flow Through the Host Rock | - Saturated flow (flow sink)<br>- Unsaturated flow (capillary diversion, drift shadow)<br>- Influx/Seepage into EBS (film flow, enhanced seepage)<br>[See also Influx/Seepage into EBS in 2.1.08.09] | 2.1.08.02.0A<br>2.2.07.18.0A<br>2.2.07.20.0A<br>2.2.07.21.0A |
| 2.2.08.05 | Condensation Forms in Host Rock | - Condensation cap<br>- Shedding<br>[See also Thermal Effects on Flow in Geosphere in 2.2.11.01] | 2.2.07.10.0A |
| 2.2.08.06 | Flow Through EDZ | - Saturated / Unsaturated flow<br>- Fracture / Matrix flow | 2.2.01.03.0A |
| 2.2.08.07 | Mineralogic Dehydration | - Dehydration reactions release water and may lead to volume changes | 2.2.10.14.0A |
| 2.2.08.08 | Groundwater Discharge to Biosphere Boundary | - Surface discharge (water table, capillary rise, surface water)<br>- Flow across regulatory boundary | 2.2.08.11.0A<br>2.3.11.04.0A |
| 2.2.08.09 | Groundwater Discharge to Well | - Human use (drinking water, bathing water, industrial)<br>- Agricultural use (irrigation, animal watering) | 1.4.07.02.0A |
| 2.2.09.00 | 2.09.CHEMICAL PROCESSES - CHEMISTRY | | |
| 2.2.09.01 | Chemical Characteristics of Groundwater in Host Rock | - Water composition (radionuclides, dissolved species, …)<br>- Water chemistry (temperature, pH, Eh, ionic strength …)<br>- Reduction-oxidation potential<br>- Reaction kinetics<br>- Interaction with EBS<br>- Interaction with host rock<br>- Future changes<br>[See also Chemistry in Tunnels in 2.1.09.04, Chemical Interactions and Evolution in 2.2.09.03]<br>[Contributes to Chemistry of Water Flowing into Repository in 2.1.09.01] | 2.2.01.02.0B<br>2.2.08.01.0B |
| 2.2.09.02 | Chemical Characteristics of Groundwater in Other Geologic Units (Non-Host-Rock)<br>- Confining units<br>- Aquifers | - Water composition (radionuclides, dissolved species, …)<br>- Water chemistry (temperature, pH, Eh, ionic strength …)<br>- Reduction-oxidation potential<br>- Reaction kinetics<br>- Interaction with other geologic units<br>- Future changes<br>[See also Chemical Interactions and Evolution in 2.2.09.04] | 2.2.08.01.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.2.09.03 | Chemical Interactions and Evolution of Groundwater in Host Rock | - Host rock composition and evolution (granite, clay, salt ...)<br>- Evolution of water chemistry in host rock<br>- Thermal effects on mineral stability<br>- Thermal effects on pore-water chemistry<br>- Chemical effects on density<br>- Interaction with EBS<br>- Reaction kinetics<br>- Mineral dissolution/precipitation<br>- Redissolution of precipitates after dry-out<br>- Paleo-hydrogeology<br>- Water residence times<br>- Redox buffering capacity of the host rock<br>- Chemical osmosis<br>[Contributes to Chemistry in Host Rock in 2.2.09.01] | 2.2.01.02.0B<br>2.2.07.14.0A<br>2.2.08.03.0B<br>2.2.08.04.0A |
| 2.2.09.04 | Chemical Interactions and Evolution of Groundwater in Other Geologic Units (Non-Host-Rock)<br>- Confining units<br>- Aquifers | - Host rock composition and evolution (granite, clay, salt ...)<br>- Evolution of water chemistry in host rock<br>- Chemical effects on density<br>- Reaction kinetics<br>- Mineral dissolution/precipitation<br>- Recharge chemistry<br>- Paleo-hydrogeology<br>- Water residence times<br>[Contributes to Chemistry in Other Geologic Units in 2.2.09.02] | 2.2.07.14.0A<br>2.2.08.03.0A |
| 2.2.09.05 | Radionuclide Speciation and Solubility in Host Rock | - Dissolved concentration limits<br>[Controlled by Chemistry in Host Rock in 2.2.09.01] | 2.2.08.07.0B |
| 2.2.09.06 | Radionuclide Speciation and Solubility in Other Geologic Units (Non-Host-Rock)<br>- Confining units<br>- Aquifers | - Dissolved concentration limits<br>[Controlled by Chemistry in Other Geologic Units in 2.2.09.02] | 2.2.08.07.0A |
| 2.2.09.50 | 2.09. CHEMICAL PROCESSES - TRANSPORT | | |
| 2.2.09.51 | Advection of Dissolved Radionuclides in Host Rock | - Flow pathways and velocity<br>- Advective properties (porosity, tortuosity, wetted surface)<br>- Dispersion<br>- Matrix diffusion<br>- Saturation<br>[See also Gas Phase Transport in 2.2.12.03] | 2.2.07.15.0B<br>2.2.08.08.0B |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.2.09.52 | Advection of Dissolved Radionuclides in Other Geologic Units (Non-Host-Rock)<br>- Confining units<br>- Aquifers | - Flow pathways and velocity<br>- Advective properties (porosity, tortuosity, wetted surface)<br>- Dispersion<br>- Matrix diffusion<br>- Saturation<br>[See also Gas Phase Transport in 2.2.12.03] | 2.2.07.15.0A<br>2.2.08.08.0A |
| 2.2.09.53 | Diffusion of Dissolved Radionuclides in Host Rock | -Gradients (concentration, chemical potential)<br>-Diffusive properties (diffusion coefficients)<br>-Connected matrix porosity<br>-Flow pathways and velocity<br>- Saturation<br>    - Ion Exclusion<br>    - Surface diffusion | 2.2.08.05.0A |
| 2.2.09.54 | Diffusion of Dissolved Radionuclides in Other Geologic Units (Non-Host-Rock)<br>- Confining units<br>- Aquifers | - Gradients (concentration, chemical potential)<br>- Diffusive properties (diffusion coefficients)<br>- Connected matrix porosity<br>- Flow pathways and velocity<br>- Saturation<br>    - Ion Exclusion<br>    - Surface diffusion | 2.2.07.17.0A |
| 2.2.09.55 | Sorption of Dissolved Radionuclides in Host Rock | - Lithology, mineralogy of rocks<br>- Surface complexation properties<br>- Ion exchange<br>    - Dissolution/precipitation of solid phases<br>    - Solid solutions/co-precipitation<br>    - Thermodynamic and kinetic data<br>    - Mineral surface areas, fracture infills<br>    - Flow pathways and velocity<br>- Saturation<br>[See also Chemistry in Host Rock in 2.2.09.01] | 2.2.08.09.0B |
| 2.2.09.56 | Sorption of Dissolved Radionuclides in Other Geologic Units (Non-Host-Rock)<br>- Confining units<br>- Aquifers | - Lithology, mineralogy of rocks<br>- Surface complexation properties<br>- Ion exchange<br>    - Dissolution/precipitation of solid phases<br>    - Solid solutions/co-precipitation<br>    - thermodynamic and kinetic data<br>    - Mineral surface areas, fracture infills<br>    - Flow pathways and velocity<br>- Saturation<br>[See also Chemistry in Host Rock in 2.2.09.01] | 2.2.08.09.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.2.09.57 | Complexation in Host Rock | - Presence of organic complexants (humates, fulvates, carbonates, …)<br>- Enhanced transport of radionuclides associated with organic complexants | 2.1.09.21.0C<br>2.2.08.06.0B |
| 2.2.09.58 | Complexation in Other Geologic Units (Non-Host-Rock)<br>- Confining units<br>- Aquifers | - Presence of organic complexants (humates, fulvates, carbonates, …)<br>- Enhanced transport of radionuclides associated with organic complexants | 2.1.09.21.0B<br>2.2.08.06.0A |
| 2.2.09.59 | Colloidal Transport in Host Rock | - Flow pathways and velocity<br>- Saturation<br>- Advection<br>- Dispersion<br>- Diffusion<br>- Sorption<br>- Colloid concentration | 2.2.08.10.0B |
| 2.2.09.60 | Colloidal Transport in Other Geologic Units (Non-Host-Rock)<br>- Confining units<br>- Aquifers | - Flow pathways and velocity<br>- Saturation<br>- Advection<br>- Dispersion<br>- Diffusion<br>- Sorption<br>- Colloid concentration | 2.2.08.10.0A |
| 2.2.09.61 | Radionuclide Transport Through EDZ | - Advection<br>- Dispersion<br>- Diffusion<br>- Ion Exclusion<br>- Sorption | 2.2.01.05.0A |
| 2.2.09.62 | Dilution of Radionuclides in Groundwater<br>- Host Rock<br>- Other Geologic Units | - Mixing with uncontaminated groundwater<br>- Mixing at withdrawal well<br>[See also Groundwater Discharge to Well in 2.2.08.09] | 2.2.07.16.0A |
| 2.2.09.63 | Dilution of Radionuclides with Stable Isotopes<br>- Host Rock<br>- Other Geologic Units | - Mixing with stable and/or naturally occurring isotopes of the same element | 3.2.07.01.0A |
| 2.2.09.64 | Radionuclide Release from Host Rock<br>- Dissolved<br>- Colloidal<br>- Gas Phase | - Spatial and temporal distribution of releases to the Other Geologic Units (due to varying flow pathways and velocities, varying transport properties)<br>[Contributions from Dissolved in 2.2.09.51/53/55, Colloidal in 2.2.09.59, Gas Phase in 2.2.12.03, EDZ in 2.2.09.61] | |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.2.09.65 | Radionuclide Release from Other Geologic Units<br>- Dissolved<br>- Colloidal<br>- Gas Phase | - Spatial and temporal distribution of releases to the Biosphere (due to varying flow pathways and velocities, varying transport properties)<br>[See also Groundwater Discharge to Biosphere Boundary in 2.2.08.08, Groundwater Discharge to Well in 2.2.08.09, Recycling of Accumulated Radionuclides in 2.3.09.55]<br>[Contributions from Dissolved in 2.2.09.52/54/56, Colloidal in 2.2.09.60, Gas Phase in 2.2.12.03] | 1.4.07.02.0A<br>2.2.08.11.0A<br>2.3.11.04.0A<br>2.3.13.04.0A |
| 2.2.10.00 | 2.10. BIOLOGICAL PROCESSES | | |
| 2.2.10.01 | Microbial Activity in Host Rock | - Formation of complexants<br>- Formation and stability of microbial colloids<br>- Biodegradation<br>- Bioaccumulation<br>[See also Complexation in Host Rock in 2.2.09.57] | 2.2.09.01.0B |
| 2.2.10.02 | Microbial Activity in Other Geologic Units (Non-Host-Rock)<br>- Confining units<br>- Aquifers | - Formation of complexants<br>- Formation and stability of microbial colloids<br>- Biodegradation<br>- Bioaccumulation<br>[See also Complexation in Other Geologic Units in 2.2.09.58] | 2.2.09.01.0A |
| 2.2.11.00 | 2.11. THERMAL PROCESSES | | |
| 2.2.11.01 | Thermal Effects on Flow in Geosphere<br>- Repository-Induced<br>- Natural Geothermal | - Thermal properties<br>- Altered saturation / relative humidity (dry-out, resaturation)<br>- Altered gradients, density, and/or flow pathways<br>- Vapor flow<br>- Condensation | 1.2.06.00.0A<br>2.2.07.11.0A<br>2.2.10.01.0A<br>2.2.10.03.0A<br>2.2.10.03.0B<br>2.2.10.11.0A<br>2.2.10.12.0A<br>2.2.10.13.0A |
| 2.2.11.02 | Thermally-Driven Flow (Convection) in Geosphere | - Convection | 2.2.10.02.0A |
| 2.2.11.03 | Thermally-Driven Buoyant Flow / Heat Pipes in Geosphere | - Vapor flow | 2.2.10.10.0A |
| 2.2.11.04 | Thermal Effects on Chemistry and Microbial Activity in Geosphere | - Mineral precipitation / dissolution<br>- Altered solubility<br>[Contributes to Chemistry in 2.2.09.01 and 2.2.09.02] | 2.2.10.06.0A<br>2.2.10.08.0A |
| 2.2.11.05 | Thermal Effects on Transport in Geosphere | - Thermal diffusion (Soret effect—Off diagonal Onsager process)<br>- Thermal osmosis | |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.2.11.06 | Thermal-Mechanical Effects on Geosphere | - Thermal expansion / compression<br>- Altered properties of fractures, faults, rock matrix | 2.2.01.02.0A<br>2.2.10.04.0A<br>2.2.10.04.0B<br>2.2.10.05.0A |
| 2.2.11.07 | Thermal-Chemical Alteration of Geosphere | - Mineral precipitation / dissolution<br>- Altered properties of fractures, faults, rock matrix<br>- Alteration of minerals / volume changes<br>- Formation of near-field chemically altered zone (rind) | 2.1.09.12.0A<br>2.2.10.06.0A<br>2.2.10.07.0A<br>2.2.10.08.0A<br>2.2.10.09.0A |
| 2.2.12.00 | 2.12. GAS SOURCES AND EFFECTS | | |
| 2.2.12.01 | Gas Generation in Geosphere | - Degassing (clathrates, deep gases)<br>- Microbial degradation of organics | 2.2.11.01.0A<br>2.2.11.02.0A |
| 2.2.12.02 | Effects of Gas on Flow Through the Geosphere | - Altered gradients and/or flow pathways<br>- Vapor/air flow<br>- Two-phase flow<br>- Gas bubbles<br>[See also Buoyant Flow/Heat Pipes in 2.2.11.03] | 2.2.10.11.0A<br>2.2.11.01.0A<br>2.2.11.02.0A |
| 2.2.12.03 | Gas Transport in Geosphere | - Gas phase transport<br>- Gas phase release from Geosphere | 2.2.11.03.0A |
| 2.2.14.00 | 2.14. NUCLEAR CRITICALITY | | |
| 2.2.14.01 | Criticality in Far-Field | - Formation of critical configuration | 2.2.14.09.0A<br>2.2.14.11.0A |
| 2.2.16.00 | 2.16 Undetected Features | | |
| 2.2.16.01 | 2.16 Undetected Geologic Features | | |
| 2.3.00.00 | 3. SURFACE ENVIRONMENT | | |
| 2.3.01.00 | 3.01. SURFACE CHARACTERISTICS | | |
| 2.3.01.01 | Topography and Surface Morphology | - Recharge and discharge areas | 2.3.01.00.0A |
| 2.3.02.01 | Surficial Soil Type | - Physical and chemical attributes | 2.3.02.01.0A |
| 2.3.04.01 | Surface Water | - Lakes, rivers, springs<br>- Dams, reservoirs, canals, pipelines<br>- Coastal and marine features<br>- Water management activities | 1.4.07.01.0A<br>2.3.06.00.0A |
| 2.3.05.01 | Biosphere Characteristics | - Climate<br>- Soils<br>- Flora and fauna<br>- Microbes<br>- Evolution of biosphere (natural, anthropogenic – e.g., acid rain)<br>[See also Climate in 1.3.01.01, Surficial Soil Type in 2.3.02.01, Microbial Activity in 2.3.10.01] | 2.3.13.01.0A |
| 2.3.07.00 | 3.07. MECHANICAL PROCESSES | | |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.3.07.01 | Past and Future Erosion | - Weathering<br>- Denudation<br>- Subsidence<br>[See also Subsidence in 1.2.02.01, Periglacial Effects in 1.3.04.01, Glacial Effects in 1.3.05.01, Surface Runoff in 2.3.08.02, and Soil and Sediment Transport in 2.3.09.53] | 1.2.07.01.0A<br>2.2.06.04.0A |
| 2.3.07.02 | Past and Future Deposition | - burial | 1.2.07.02.0A |
| 2.3.07.03 | Animal Intrusion into Repository | | 2.3.09.01.0A |
| 2.3.08.00 | 3.08. HYDROLOGIC PROCESSES | | |
| 2.3.08.01 | Precipitation | - Spatial and temporal distribution<br>[See also Climate Change in 1.3.01.01]<br>[Contributes to Infiltration in 2.3.08.03] | 2.3.11.01.0A |
| 2.3.08.02 | Surface Runoff and Evapotranspiration | - Runoff, impoundments, flooding, increased recharge<br>- Evaporation<br>- Transpiration (root uptake)<br>[See also Climate Change in 1.3.01.01, Erosion in 2.3.07.01]<br>[Contributes to Infiltration in 2.3.08.03] | 2.3.11.02.0A<br>2.2.06.04.0A |
| 2.3.08.03 | Infiltration and Recharge | - Spatial and temporal distribution<br>- Effect on hydraulic gradient<br>- Effect on water table elevation<br>[See also Topography in 2.3.01.01, Surficial Soil Type in 2.3.01.02]<br>[Contributes to Effects of Recharge in 2.2.08.03] | 2.3.11.03.0A |
| 2.3.09.00 | 3.09. CHEMICAL PROCESSES - CHEMISTRY | | |
| 2.3.09.01 | Chemical Characteristics of Soil and Surface Water | - Altered recharge chemistry (natural)<br>- Altered recharge chemistry (anthropogenic – e.g., acid rain)<br>[Contributes to Chemical Evolution of Groundwater in 2.2.09.04] | 1.4.01.03.0A<br>1.4.06.01.0A |
| 2.3.09.02 | Radionuclide Speciation and Solubility in Biosphere | - Dissolved concentration limits | 2.2.08.07.0C |
| 2.3.09.03 | Radionuclide Alteration in Biosphere | - Altered physical and chemical properties<br>- Isotopic dilution | 2.3.13.02.0A<br>3.2.07.01.0A |
| 2.3.09.50 | 3.09. CHEMICAL PROCESSES - TRANSPORT | | |
| 2.3.09.51 | Atmospheric Transport Through Biosphere | - Radionuclide transport in air, gas, vapor, particulates, aerosols<br>- Processes include: wind, plowing, irrigation, degassing, saltation, precipitation | 3.2.10.00.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.3.09.52 | Surface Water Transport Through Biosphere | - Radionuclide transport and mixing in surface water<br>- Processes include: lake mixing, river flow, spring discharge, aeration, sedimentation, dilution<br>[See also Surface Water in 2.3.04.01] | 2.3.04.01.0A |
| 2.3.09.53 | Soil and Sediment Transport Through Biosphere | - Radionuclide transport on soil and sediments<br>- Processes include: fluvial (runoff, river flow), eolian (wind), glaciation, bioturbation (animals)<br>[See also Erosion in 2.3.07.01, Deposition in 2.3.07.02] | 2.3.02.03.0A<br>2.3.09.01.0A |
| 2.3.09.54 | Radionuclide Accumulation in Soils | - Leaching/evaporation from discharge (well, groundwater upwelling)<br>- Deposition from atmosphere or water (irrigation, runoff) | 2.3.02.02.0A |
| 2.3.09.55 | Recycling of Accumulated Radionuclides from Soils to Groundwater | [See also Radionuclide Release in 2.2.09.65] | 1.4.07.03.0A |
| 2.3.10.00 | 3.10. BIOLOGICAL PROCESSES | | |
| 2.3.10.01 | Microbial Activity in Biosphere | - Effect on biosphere characteristics<br>- Effect on transport through biosphere | |
| 2.3.11.00 | 3.11. THERMAL PROCESSES | | |
| 2.3.11.01 | Effects of Repository Heat on Biosphere | | 2.3.13.03.0A |
| 2.4.00.00 | 4. HUMAN BEHAVIOR | | |
| 2.4.01.00 | 4.01. HUMAN CHARACTERISTICS | | |
| 2.4.01.01 | Human Characteristics | - Physiology<br>- Metabolism<br>- Adults, children<br>[Contributes to Radiological Toxicity in 3.3.06.02] | 2.4.01.00.0A |
| 2.4.01.02 | Human Evolution | - Changing human characteristics<br>- Sensitization to radiation<br>- Changing lifestyle | 1.5.02.00.0A<br>3.3.06.02.0A |
| 2.4.04.00 | 4.04. LIFESTYLE | | |
| 2.4.04.01 | Human Lifestyle | - Diet and fluid intake (food, water, tobacco/drugs, etc.)<br>- Dwellings<br>- Household activities<br>- Leisure activities<br>[See also Land and Water Use in 2.4.08.01]<br>[Contributes to Ingestion in 3.3.04.01, Inhalation in 3.3.04.02, External Exposure in 3.3.04.03] | 2.4.04.01.0A<br>2.4.07.00.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 2.4.08.00 | 4.08. LAND AND WATER USE | | |
| 2.4.08.01 | Land and Water Use | - Agricultural (irrigation, plowing, fertilization, crop storage, greenhouses, hydroponics)<br>- Farms and Fisheries (feed, water, soil)<br>- Urban / Industrial (development, energy production, earthworks, population density)<br>- Natural / Wild (grasslands, forests, bush, surface water) | 2.4.08.00.0A<br>2.4.09.01.0B<br>2.4.09.02.0A<br>2.4.10.00.0A |
| 2.4.08.02 | Evolution of Land and Water Use | - New practices (agricultural, farming, fisheries)<br>- Technological developments<br>- Social developments (new/expanded communities) | 1.4.08.00.0A<br>1.4.09.00.0A<br>2.4.09.01.0A |
| 3.0.00.00 | 3. RADIONUCLIDE / CONTAMINANT FACTORS (BIOSPHERE) | | |
| 3.1.00.00 | 1. CONTAMINANT CHARACTERISTICS | | |
| 3.2.00.00 | 2. RELEASE / MIGRATION FACTORS | | |
| 3.3.00.00 | 3. EXPOSURE FACTORS | | |
| 3.3.01.00 | 3.01. RADIONUCLIDE / CONTAMINANT CONCENTRATIONS | | |
| 3.3.01.01 | Radionuclides in Biosphere Media | - Soil<br>- Surface Water<br>- Air<br>- Plant Uptake<br>- Animal (Livestock, Fish) Uptake<br><br>[Contributions from Radionuclide Release from Geologic Units in 2.2.09.65, Transport Through Biosphere in 2.3.09.51/52/53/54/55] | 3.3.02.01.0A<br>3.3.02.02.0A<br>3.3.02.03.0A |
| 3.3.01.02 | Radionuclides in Food Products | - Diet and fluid sources (location, degree of contamination, dilution with uncontaminated sources)<br>- Foodstuff and fluid processing and preparation (water filtration, cooking techniques)<br><br>[See also Land and Water Use in 2.4.08.01, Radionuclides in Biosphere Media in 3.3.01.01] | 3.3.01.00.0A |
| 3.3.01.03 | Radionuclides in Non-Food Products | - Dwellings (location, building materials and sources, fuel sources)<br>- Household products (clothing and sources, furniture and sources, tobacco, pets)<br>- Biosphere media<br><br>[See also Land and Water Use in 2.4.08.01, Radionuclides in Biosphere Media in 3.3.01.01] | 3.3.03.01.0A |
| 3.3.04.00 | 3.04. EXPOSURE MODES | | |
| 3.3.04.01 | Ingestion | - Food products<br>- Soil, surface water | 3.3.04.01.0A |

| UFD FEP Number | Phenomena | Associated Processes | YMP FEP Database |
|---|---|---|---|
| 3.3.04.02 | Inhalation | - Gases and vapors<br>- Suspended particulates (dust, smoke, pollen) | 3.3.04.02.0A |
| 3.3.04.03 | External Exposure | - Non-Food products<br>- Soil, surface water | 3.3.04.03.0A |
| 3.3.06.00 | 3.06. TOXICITY / EFFECTS | | |
| 3.3.06.01 | Radiation Doses | - Exposure rates (ingestion, inhalation, external exposure)<br>- Dose conversion factors<br>- Gases and vapors<br>Suspended particulates (dust, smoke, pollen) | 3.3.05.01.0A<br>3.3.08.00.0A |
| 3.3.06.02 | Radiological Toxicity and Effects | - Human health effects from radiation doses | 3.3.06.00.0A |
| 3.3.06.03 | Non-Radiological Toxicity and Effects | - Human health effects from non-radiological toxicity | 3.3.07.00.0A |

# APPENDIX D: UNCERTAINTY IN DEGRADATION OF WASTE FORMS

The relative performance of the generic waste forms in the four generic disposal environments is amenable to quantitative analysis. As noted previously, the UFD Campaign is developing the capability to model different disposal environments and waste form options [12]. The Generic Disposal System (GDS) Modeling activity of UFD has conducted some demonstration analyses for SNF and standard HLW borosilicate glass [12]. Here we use the results from the clay/shale repository demonstration to make several points that will be reassessed in future analyses. In addition, we draw upon some preliminary studies on different treatment options with more advanced waste forms that were conducted in the 1990s [50-52]. Finally, waste form behavior from the Yucca Mountain license application is also presented [15].

## D.1 SNF and HLW Degradation Rates in Clay/Shale

For SNF in a reducing environment, estimates of degradation range from $10^{-8}$ to $10^{-6}$ with a mode of $10^{-7}$ $yr^{-1}$ (i.e., triangular distribution). For HLW borosilicate glass in a reducing environment, estimates of degradation range from $3.4 \times 10^{-6}$ to $3.4 \times 10^{-3}$ $yr^{-1}$ with a mean of $10^{-4}$ $yr^{-1}$, assuming a loguniform distribution (and not considering decreases in degradation as the fluid around the HLW saturates with silica) [12, §3.1.2.5]. This mean value is three orders of magnitude greater than the mode of the SNF degradation rate in a reducing environment, and thus HLW would seemingly release a far greater amount of radionuclides into the near-field per unit time in reducing environments.

However, there is an important caveat. At high waste form degradation rates greater than $2 \times 10^{-5}$ $yr^{-1}$, radionuclide release from the clay/shale disposal system is controlled by radionuclide transport processes in the remainder of the EBS or through the natural barrier in the far field in a clay/shale disposal system (Figure D-1). Only at very low degradation rates of SNF in an anoxic environment, does the SNF waste form control the mass flux and release rate (and the annual dose) from a clay/shale disposal system. Hence the difference in release rates is actually reduced to two orders of magnitude.

Figure D-1 also shows the sensitivity to the waste form fractional degradation rate for PWR SNF with different burn-up, disposed at 30-yr following reactor discharge. The results of Figure D-1 show essentially a linear dependence on burn-up. This is because $^{129}$I is the dominant radionuclide in a clay/shale repository system and, as a fission product, its inventory in SNF is approximately a linear function of burn-up.

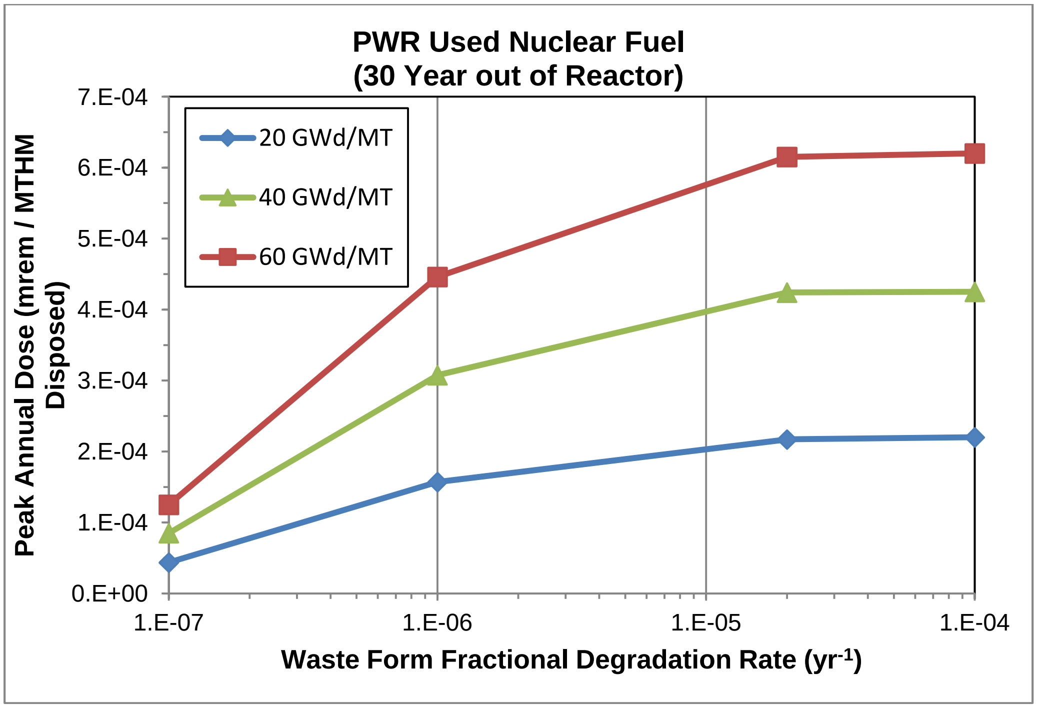


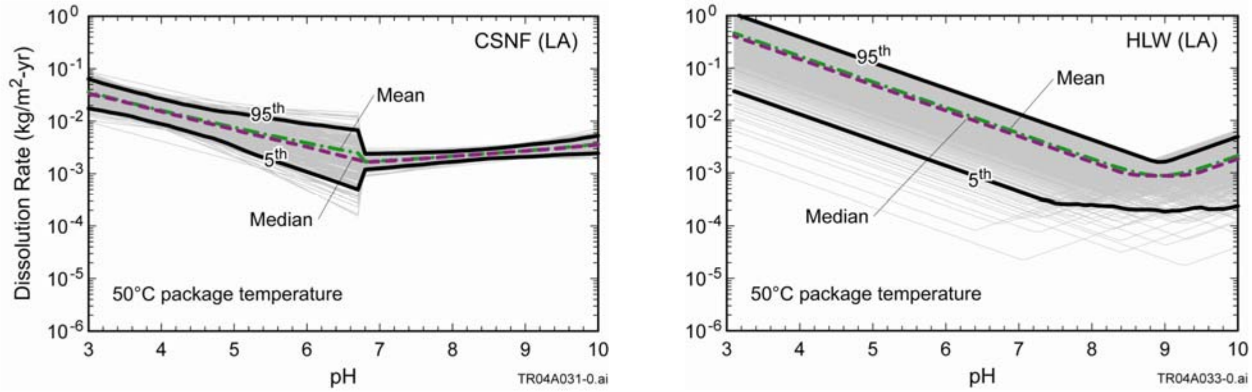
**Figure D-1. UFD sensitivity analysis for clay repository – effect of SNF burn-up and fractional degradation rate [12, Figure 3.3-30].**

## D.2 SNF and HLW Degradation Rates in Unsaturated Zone of Tuff

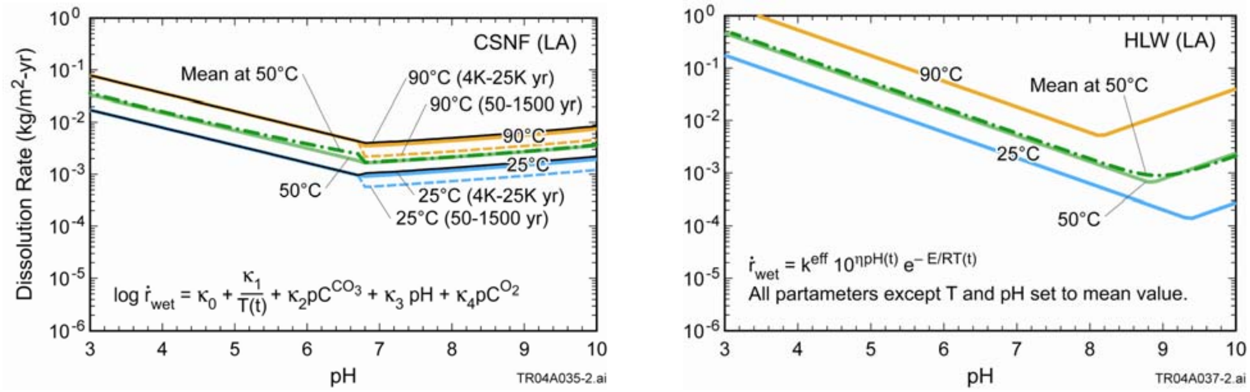
The simple results from the clay/shale disposal system shed light on how other components of a disposal system can compensate for seemingly adverse conditions in an oxygenated environment. For the Yucca Mountain disposal system in the unsaturated zone, the fractional release rate of HLW in an oxygenated environment was similar to that in an anoxic environment (~4 $\times 10^{-4}$ $\text{yr}^{-1}$ at neutral pH using a mass normalized surface area ($\bar{A}_{HLW}^{surf}$) of 5.98 $\times 10^{-2}$ $\text{m}^2/\text{kg}$ in Figure D-2d). The fractional release rate of SNF was ~20 times larger at neutral pH (~$8 \times 10^{-3}$ $\text{yr}^{-1}$ assuming a mass normalized surface area of 3.96 $\text{m}^2/\text{kg}$ for values in Figure D-2c).[21] Also, note that uncertainty of fractional release rate was generally larger for the borosilicate glass waste form for the reprocessed HLW than for the SNF (Figures D-2b versus D-2a). That is, reprocessing the SNF to produce HLW borosilicate glass did not reduce uncertainty. However, neither rate nor uncertainty was important in the TSPA-LA (Table B-1) because other components of the Yucca Mountain disposal system, particularly the slow degradation of the package compensated for the high release rates.

---

[21] The difference was not larger because the SNF degradation rate ($\dot{r}_{CSNF}$ —$\text{kg/m}^2\text{-yr}$) in the oxygenated environment of the Yucca Mountain disposal system was generally smaller than the HLW degradation rate (Figure D-2c and D-2d).



(a) Sampled commercial SNF degradation (b) Sampled HLW degradation



(c) Commercial SNF degradation variation with *t*, *T*, pH (d) HLW degradation with *T* and pH

**Figure D-2. Waste form degradation rates as a function of temperature and pH in TSPA-LA.**

## D.3. Comparison of Robust and Standard SNF

In 1993 and 1995, DOE explored different treatment options for its waste—DOE-owned SNF and Defense HLW—by examining its behavior in salt, granite, and tuff repository environments [50-52]. The studies were a precursor of the type of studies the UFD Campaign will be exploring in the future. Here, we extract some of the results comparing the performance of UOX SNF with fuel from the high-temperature, gas-cooled (HTGR) Fort St. Vrain demonstration reactor considered by the BRC, as noted in the Chapter 1.

### D.3.1 EPA Standard for a Generic Disposal System, 40 CFR 191

The early studies in 1993 and 1994 used the generic standards for radioactive waste disposal promulgated by EPA in its 40 CFR 191 [53] and NRC in its implementing regulation 10 CFR 60, to establish post-closure performance requirements. In 40 CFR 191, the performance measure was cumulative release ($R$) evaluated at $10^4$ yr at a boundary located at the surface and at a vertical boundary 5 km from the source (Table D-1) The cumulative release was normalized by dividing by (a) EPA derived limits $L_r$ for certain radionuclides and (b) mass placed in the repository expressed as a waste unit factor. The limits $L_r$ were set to allow no more than 1000 premature cancer deaths over $10^4$ yr for a 100,000-MTHM repository from aqueous releases [53; 54, §7.8; 55-57]. By normalizing the cumulative release by the mass in the repository, the Containment Requirements did not penalize use of large repositories, which inherently creates a large source-term [33; 54].

## D.3.2 NRC Implementing Regulation for a Generic Disposal System, 10 CFR 60

In 1983, NRC promulgated technical criteria to 10 CFR 60 [58] that set deterministic performance objectives on subsystems of the geologic disposal system (Table D-1). NRC thought quantitative performance objectives on subsystems would ensure use of multiple barriers and defense in depth [7, p.55737; 56; 58], an aspect of geologic disposal intended to address uncertainty, as discussed further in Chapter 2.

**Table D-1. Regulatory basis for generic geologic disposal systems in US.**

| Regulation | Requirement | Measure | Limit |
|---|---|---|---|
| 40 CFR 191 (Generic) 1993 | 1.Cumulative Release | Distribution of expected cumulative release $R$ from retained scenario classes after $10^4$ yr at surface or 5 km boundary from perimeter of waste, normalized by mass fraction of long-lived radionuclides disposed in repository ($M_r$/1000 tonnes) and EPA derived limits $L_r$, based on population exposure. | Limiting distribution defined by<br>$R \leq 1$ for probability ($\wp$) $\geq 0.1$<br>$R \leq 10$ for $0.1 > \wp \geq 0.001$ |
| | 2. Individual Protection | Individual committed effective dose equivalent (CEDE—dose received over 50 yr from 1 yr exposure) for undisturbed scenario over $10^4$ yr using mean model parameters | <15 mrem/yr for $t < 10^4$ yr |
| | 3. Groundwater Protection | Concentration for undisturbed scenario at 5 km boundary over $10^4$ yr using mean model parameters | Radioactivity < limits in 40 CFR 141 (Clean Water Act) |
| 10 CFR 60 (Generic) 1983 | 4. Performance of barriers [*] | Performance standards for natural system barrier (groundwater travel time, $\tau^{gw}$) and EBS (minimum package life, ${}^{min}\tau^{WPfail}$, and EBS release rates, $\overline{m}_r^{EBS}$, for each radionuclide $r$ based on total inventory of each radionuclide $M_r$ | $\overline{\tau}^{gw} < 1000$ yr<br>$300 \text{ yr} < {}^{min}\tau^{WPfail} < 1000 \text{ yr}$<br>$\overline{m}_r^{EBS} < \max\{m_r^{\text{limit}}, m_{total}^{\text{limit}}\}$<br>$\dot{m}_r^{\text{limit}} = M_r(t = 10^3 \text{ yr})/10^5 \text{ yr}$<br>$\dot{m}_{total}^{\text{limit}} = \sum_r^{n_r} M_r(t = 10^3 \text{ yr})/10^8 \text{ yr}$ |

[*] 40 CFR 191also has other assurance requirements but they are not applicable to a repository for commercial SNF

## D.3.3 Fort St. Vrain Fuel Characteristics

Fort St. Vrain fuel consists of uranium ($^{233}$U) and thorium carbide microspheres surrounded by low density porous carbon layer to provide volume to accumulate fission product gases, a layer of high-density isotropic carbon, a ceramic layer of silicon carbide (SiC), which highly resistant to both oxidation and moisture degradation, and then another layer of high-density isotropic carbon. The microspheres are imbedded into a graphite matrix binder to form "compacts." The compacts are inserted into fuel holes in a graphite block. Graphite blocks form the core of the reactor.

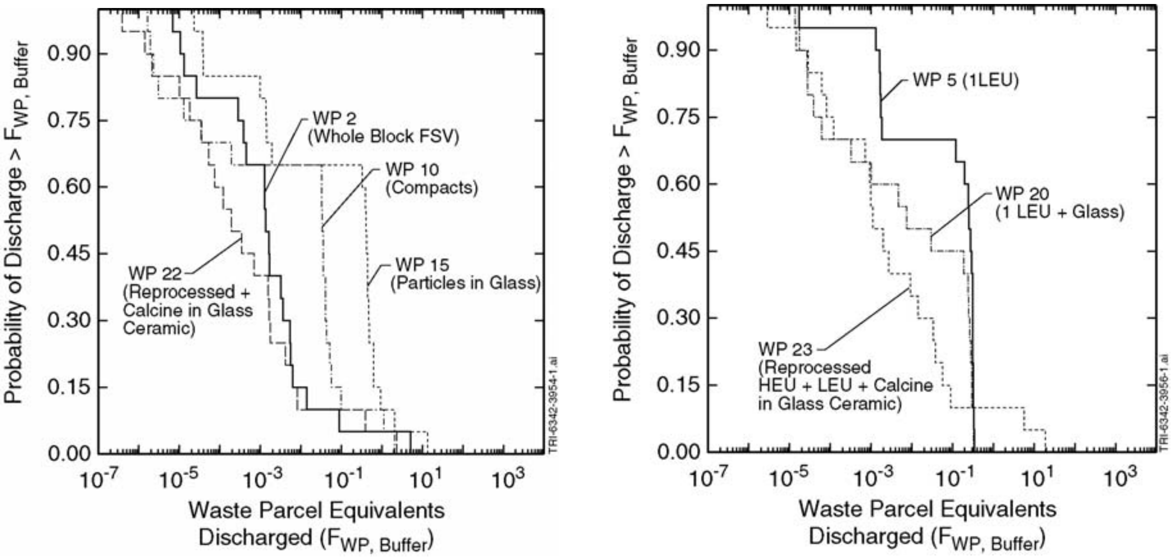
Based on examination of the microspheres after irradiation, the fraction of microspheres breached was between 0.003 and 0.005 in the first 726 block elements and between 0.0003 and 0.0005 in the later 1482 block elements [50, p. 11-48]. Based on weighted averages, the distribution of particles that fail over $10^4$ yr in an anoxic environment such as a granite disposal system was expressed with a median of 0.0016. In contrast, the fraction of zircaloy cladding on commercial SNF perforated has a mean of 0.022 [51, Figure 8-3] (Table D-2). Hence, SiC coating on fuel microspheres could represent a significant improvement in repository behavior, irrespective of moving to advanced fuel cycles with partitioning and transmutation.

**Table D-2. Cumulative distribution of fraction of cladding on SNF breached.**

| | | Distribution of fraction breached | | | | |
|---|---|---|---|---|---|---|
| SNF Type | Condition | 0% | 50% | mean | 90% | 100% |
| Fort St. Vrain* | As is (graphite blocks cut to fit canisters) | 0.001 | 0.0016 | | 0.005 | 1.00 |
| | Compacts removed, graphite binder burned off | 0.050 | 0.070 | | 0.20 | 1.00 |
| UOX SNF** | As is | 0.001 | 0.01 | 0.022 | | 0.10 |

*Source [50, p. 11-48]
**Source [51, Figure 8-3]

Using the EPA cumulative release measure of 40 CFR 191 for the first $10^4$ yr (Table D-2), the SiC coated Fort St. Vrain (FSV) SNF has better performance at the backfill buffer around the package for a crystalline geologic disposal system (Figure D-3).



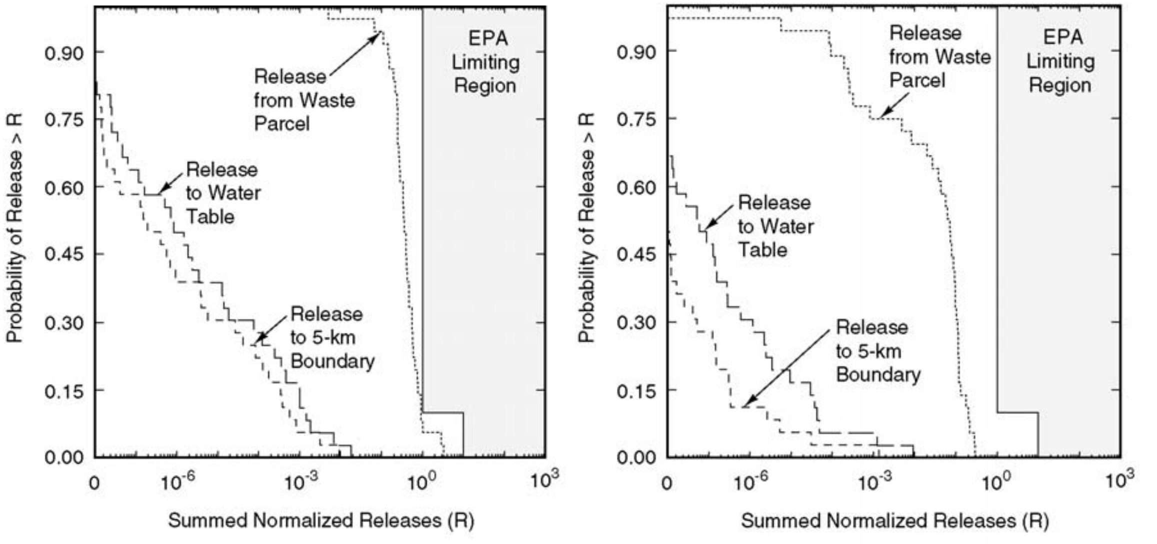
(a) Fort St. Vrain (FSV) (b) UOX low-enchiched uranium (LEU) SNF

**Figure D-3. Complementary cumulative distribution function of number of waste packages equivalents discharged into backfill-buffer for the crystalline rock disposal system (conditional on one intrusion to form a fast path for fluid flow to aquifer) [50, Figures 16.5-4 & 16.5-6].**

## D.3.4 Results

In a volcanic tuff disposal system, the Fort St. Vrain SNF performed about as well as N-Reactor SNF (used for the production of Pu for the weapons program) with ~50% failed zircaloy cladding and only somewhat worse than UOX SNF with 2.2% breached zircaloy cladding (Table D-2). This improved behavior occurred despite placing Fort St. Vrain SNF in a package without a corrosion resistant layer of Alloy 825 (precursor to Alloy 22 used for TSPA-LA), while both N-Reactor SNF and the UOX SNF were in packages with a layer of Inconel Alloy 825 (Figure D-4).

The degradation rate of the fuel matrix for the Fort St. Vrain and UOX SNF was similar, and so the integrity of the zircaloy cladding or SiC layer was the primary determining factor.



(b) (a) Fort St. Vrain SNF (no Alloy 825 in package) ` (b) UOX SNF

**Figure D-4. Mean complementary cumulative distribution functions for groundwater release from waste, water table, and 5-km boundary at $10^4$ yr for tuff disposal system [51, Figure 15.3-7].**

For the tuff disposal system, the variability in release in these early studies was influenced most by the uncertainty in (1) parameters related to the package (i.e., corrosion rate of the Alloy 825 layer and fraction of packages in contact with rubble from the disposal drift); (2) infiltration/percolation parameters through the unsaturated zone (i.e., minimum infiltration, return period for climate change, permeability of tuff host layer); and (3) geochemical parameters (i.e., adsorption of Pu on rust of package and U solubility), which is similar to the finding for the TSPA-LA (Table B-1).

For the salt, granite, and tuff disposal systems, the DOE studies in the 1990s concluded [50, Table 16.11-1; 51, Table 15.3-2]:

> The performance of DOE spent fuels straddles the performance of pressurized water reactor (PWR) spent fuels when the measure is the EPA summed normalized release.The rank order from best to worst is (order controlled by integrity or durability of cladding)
>
> 1. Fort St. Vrain graphite fuels (uranium and thorium carbide with silicon carbide coating) (similar to N-Reactor fuel when there is no lnconel Alloy 825 layer in disposal package)
> 2. Shippingport (uranium dioxide fuel with zircaloy cladding)
> 3. PWR (uranium dioxide fuel with zircaloy cladding)
> 4. N-Reactor (uranium metal fuel with damaged zircaloy cladding)
> 5. ATR [advanced test reactor] fuel (uranium metal fuel with aluminum cladding)

Although the mean value of the durability or integrity of the cladding was important for ranking the release from individual SNF, the uncertainty in the durability or integrity of the cladding about the mean was not important in explaining the spread in the cumulative-release performance measure [50, Tables 16.5-2 & 16.5-3; 51, Tables 15.7-1, 15.7-2, and 15.7-3].

Both the existing and new waste form required a characterization of the cladding integrity (parameter uncertainty). Typically, the characterization requires experiments to generate probabilistic distributions representing the uncertainty of degradation rates. Furthermore, the degradation model of the Fort St. Vrain SNF had to account for a multiple protective layers (with the SiC layer as the primary layer) for the uranium-thorium carbide matrix; thus, the model complexity was somewhat increased. Finally, no mechanisms of degradation in a repository environment were known to exist for the SiC layer, which represents scenario uncertainty. Experimentation would have to explore potential modes of degradation. In other words, new waste forms from alternative nuclear fuel cycles also come with scenario, model, and parameter uncertainties that are just as formidable to address as those for existing waste forms.