THE SIGNIFICANCE OF TECTONIC EVENTS AND PROCESSES ON THE LONG-TERM ISOLATION OF HIGH-LEVEL RADIOACTIVE WASTES

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ABSTRACT

The development of tectonic scenarios for a high-level radioactive waste repository will depend on both the probability of occurrence of a tectonic event and the relationship between the tectonic event and those factors which may be important in assessing repository performance. Estimation of probability of occurrence requires use of as much of the available information as possible regarding the current tectonic regime of each prospective site. For those events which are found to be credible, judgments are required as to how the tectonic events could impact hydrologic, geochemical or mechanical performance factors. Example generic relationships between performance factors and tectonic events are presented to show the type of information that will be important in developing tectonic scenarios.

INTRODUCTION

The purpose of this paper is to outline the thought process that will need to be understood when developing potential tectonic disruptive scenarios for a high-level radioactive waste repository. This process not only includes the evaluation of tectonic event probability but also an evaluation of whether a given tectonic event can impact the amount of radionuclide releases projected for a given site. Thus, a determination must be made regarding the effect that a tectonic event can have on the barriers which prevent the release of radionuclides.

First we will examine some general relationships between tectonic phenomena and those factors which may be important to long-term isolation of high-level radioactive waste in an underground repository. Second, methods will be proposed which can be used to determine the probability of tectonic events and processes. Finally, a site specific example will be developed showing how the process could be applied to developing a specific tectonic scenario.

As identified in the Code of Federal Regulations (CFR) 10 CFR Part 60, 10 CFR Part 960, and 40 CFR Part 191, the evaluation of postclosure repository performance must consider the effects of both anticipated and unanticipated events and processes over 10,000 years. As part of this evaluation, disruptive scenarios need to be developed accounting for both potential natural phenomena and human interference, and their effects on repository performance.

Scenario Selection Procedure

The evaluation of disruptive scenarios can be broken into various components, including for example, scenario description, scenario screening, and evaluation of scenario release significance. First phenomena that will need to be considered for the postclosure time period are identified. With respect to tectonic phenomena, these include permanent fault displacement, vibratory ground motion, magmatic activity, folding, tilting, uplift and subsidence. Because the processes of folding, tilting, uplift (without faulting), and subsidence (without faulting) are less likely to lead to disruption of a repository during the next 10,000 years, they are not discussed here. Next, these phenomena must be screened to determine which are most important. In parallel to this activity, the factors significant to determining the amount of radionuclide release must be identified. Scenarios are then formulated by combining events that survive screening with radionuclide release factors (such as ground-water travel time, retardation etc.) that govern the amount of potential releases to the accessible environment. Each scenario is then evaluated to assess the significance of the scenario with respect to determining the full spectrum of releases for a given site. For the purposes of illustration, the following pages discuss in detail the evaluation of fault displacement followed by a brief discussion of magmatic scenarios.

Fault Scenarios

The evaluation of fault scenarios depends on the way that faulting affects the factors significant to repository performance. The performance factors that are important include the amount of waste that can be dissolved into the ground water, the time of radionuclide travel through the natural barriers, and the waste-package lifetime, if it is comparable to, or greater than, the radionuclide-travel time. Examples of site conditions and characteristics which could affect the amount of waste to be dissolved, radionuclide-travel time, and waste-package lifetime are shown in Table I. This list was developed as part of the Department of Energy's Multiattribute Utility Analysis of Sites Nominated for Characterization for the First Radioactive-Waste Repository (1). The conditions and characteristics include the expected thermal, mechanical, geohydrologic, geochemical, and

TABLE I

Examples of Site Condition and Characteristics That Could Affect Repository-Performance Factors Such as the Amount of Waste to be Dissolved, Radionuclide Travel Time, and Waste Package Lifetime

1. Conditions affecting waste-package lifetime.
   a. Thermal conditions
   b. Mechanical conditions (thermomechanical stresses, ground movement)
   c. Volume of, and replacement rate for, fluids near waste package
   d. Corrosion rate

2. Local fluid conditions affecting the rate of release from the engineered-barrier system.
   a. Ground water flux through the host rock or seepage into repository
   b. Number of packages exposed to water

3. Local chemical conditions affecting the rate of release from the engineered-barrier system.
   a. Radionuclide solubility
   b. Waste-form dissolution rate
   c. Thermal effects on leach rates and local chemical conditions

4. Conditions affecting ground-water movement to accessible environment.
   a. Rock characteristics that determine ground-water pathways
   b. Hydraulic properties
   c. Heat gradients
   d. Unsaturated flow characteristics
   e. Constraints due to regional flow conditions

5. Conditions affecting retardation.
   a. Sorption
   b. Precipitation
   c. Physical retardation
   d. Dispersion

6. Other conditions affecting radionuclide travel time.
   a. Diffusion transport
   b. Transport of gases

other conditions resulting from the pre-waste emplacement characteristics of the site, the natural changes in these characteristics, and the changes induced by the excavation of the repository and the emplacement of heat-generating wastes. In developing potential disruptive scenarios, the list of site conditions and characteristics in Table I are examples of those that must be altered for the disruptive event to potentially impact radionuclide releases. Specific examples of how fault displacement could affect such factors are listed in Table II. These examples show how faulting may impact the performance of a barrier which prevents the release of radionuclides. The right-hand column of Table II lists the specific site condition and characteristics affected from Table I.

As shown in Table II, fault displacement could affect ground-water travel time by modifying the permeability of existing pathways or by creating new ones. In extreme cases, large-scale movement on a major fault across the repository might create a direct flow path from the repository to the accessible environment. Strong vibratory ground motion from these types of events could also modify ground-water flow depending on state of stress, material properties, and pore pressures within the affected rock. In addition to large fault movements in the controlled area, ground-water travel time could also be indirectly affected by faulting outside the controlled area if the regional flow is affected.

As another example, fault-induced changes in flow paths could affect water flux past waste packages. Fault displacement could connect transmissive units that are otherwise unconnected. In these instances, an evaluation of increases in the flux through the repository could involve flow direction, the permeability of the fault zone and aquifers, the number of waste packages affected by the fault displacement, and whether the changes are temporary or permanent.

Fault displacement may introduce new sources of water into the repository and along flow paths, thereby altering the geochemical setting. Such alteration could affect the solubility of waste, corrosion of the waste packages, or radionuclide retardation along flow paths. Retardation along flow paths could also be affected by physical changes in the fault zone, such as the alteration of a fault zone into a high transmissive pathway. The waste-containment time may be shortened if the fault intersects the repository and disrupts waste packages.

In developing disruptive scenarios it is important to integrate the actual geologic, hydrologic, chemical, and mechanical characteristics of the site, and the empirical evidence of the effects of faulting on, for example, hydraulic conditions. This may include examples of mine floodings or ground-water elevation changes which have been observed after earthquakes.

TABLE II

Examples of How Fault Displacement Could Affect the Repository Performance Factors Listed in Table I	Site Conditions and Characteristics Affected
From Table I	
o Temporary or permanent increase of available water or the rate of water flux through a percentage of the repository, including potential aquifer connections, by direct shearing (displaced stratigraphic units).	1c 2a 2b
o Creation or enlargment of perched water which may increase flux across the waste, by displaced stratigraphic units.	1c 2a 2b
o Direct shearing of a small percentage of the waste packages.	1b
o Early failure of waste package from over-stressing by ground motion.	1b
o Deleterious alteration of the chemistry of the ground-water through the repository resulting in increased dissolution of the waste, or shortened container lifetime due to changes in ground water composition (increased rate of corrosion), by bringing in new sources of ground-water.	1d
o Alteration of hydraulic properties of existing pathways due to high strain deformation (high vibratory ground motion).	4b
o Alteration of existing pathways, resulting in a highly permeable zone (increased gradient or conductivity) by direct shearing of stratigraphic units.	4b
o Create new pathways resulting in a highly permeable zone by direct shearing of stratigraphic units.	4a

Probability of Faulting

Probabilities of fault displacement occurrence depend on several factors. Available evidence indicates that most fault offsets in the shallow crust occur on pre-existing faults (2). The likelihood therefore, of generating a new fault in unfractured material may not be credible, particularly in highly faulted geologic regions. Two broad categories of data can be used to generate probabilities of fault displacement; (1) the neotectonic history of the region and, (2) measurements of ongoing deformation. Specific types of information to estimate probabilities include the state of stress, rates of uplift and subsidence, patterns and levels of instrumental and historic seismicity, and estimated slip rates and other geologic data for faults which have moved in the current tectonic regime.

It is also important to assess physical dimensions of potential faulting. Faulting capable of rupture lengths of tens of kilometers and displacements of several meters should be considered differently than much smaller events. While the potential earthquake magnitude and rupture dimensions of a large event may be significantly greater than that of a small event, the probability of occurrence of a small event may be many orders of magnitude larger than that of a large event. Additionally, fault displacement within the repository is likely to have considerably more impact on factors important to performance than an event that occurs outside the repository, because the barriers important to isolation can be directly affected. It is difficult to conceive of small events significantly impacting normal repository performance unless a given site has the potential for so many small events that their cumulative effect is significant. Additionally, the probability of a large event occurring within the repository is likely to be extremely low given the relatively small size of the repository. However, because of the relatively long period of interest (10,000 years), the probabilities assigned to fault displacement are likely to be highly uncertain.

An example of potential fault scenarios is provided for the Yucca Mountain site in Nevada. Table III lists both the expected hydrologic conditions at Yucca Mountain along with tye types of questions that need to be addressed to develop fault displacement scenarios. Table III was developed using information contained in the 1986 Environmental Assessment for the Yucca Mountain Site (3) and other references such as Ross (1986) (4) who presented seventeen categories of sequences which could lead to failure of one or more barriers important to isolation of radionuclides. The site specific questions listed will need to be addressed, in addition to probability of fault displacement occurrence, prior to final development of potential faulting scenarios. Considering that the probability of occurrence of the event is relatively high at the Yucca Mountain site (see below), the site specific questions would be the primary mechanism to determine if fault displacement events would need to be considered as disruptive scenarios. As can be seen, the answers to these types of questions are not straightforward. The general strategy that will likely be used will be to compare current hydrologic characteristics that reflect the cumulative effects of Quaternary tectonism to determine if significant changes to factors such as flux or water table elevation could occur.

For the Yucca Mountain site, information such as earthquake recurrence statistics, age of last fault movement, and slip rates for Quaternary faults can be used to assess the probability of faulting. This type of information is shown on Fig. 1 and is described below. Figure 1 is a plot showing the cumulative number of earthquakes per year versus earth-

TABLE III

Expected Conditions at Yucca Mountain

1. Repository in unsaturated zone, from 185 meters to 300 meters above the water table.

2. Based on conceptual model for ground-water movement the flux of water is postulated to be vertically downward and through the rock matrix rather than through fractures in the unsaturated zone.

3. Fracture versus matrix flow is dependent on degree of rock saturation.

4. There is some uncertainty regarding the potential for lateral diversion of flow in the unsaturated zone at stratigraphic boundaries, and there is uncertainty regarding the potential for small bodies of perched water at the site.

5. Waste package lifetime estimated to be at least 3,000 years.

6. Retardation of many radionuclides both in the unsaturated and saturated zones.

Site Specific Questions to be Addressed

1. If fault displacement occurs, how high would the water table rise? For how long?

2. Could fault displacement change flux above or below repository? How?

3. Could fault displacement alter any lateral diversion and bring more water through a portion of the repository?

4. Could fault displacement affect flux through fractures?

5. Could fault displacement intersect and shear waste packages? How many?

6. Could fault displacement alter retardation in the unsaturated or saturated zone? How?

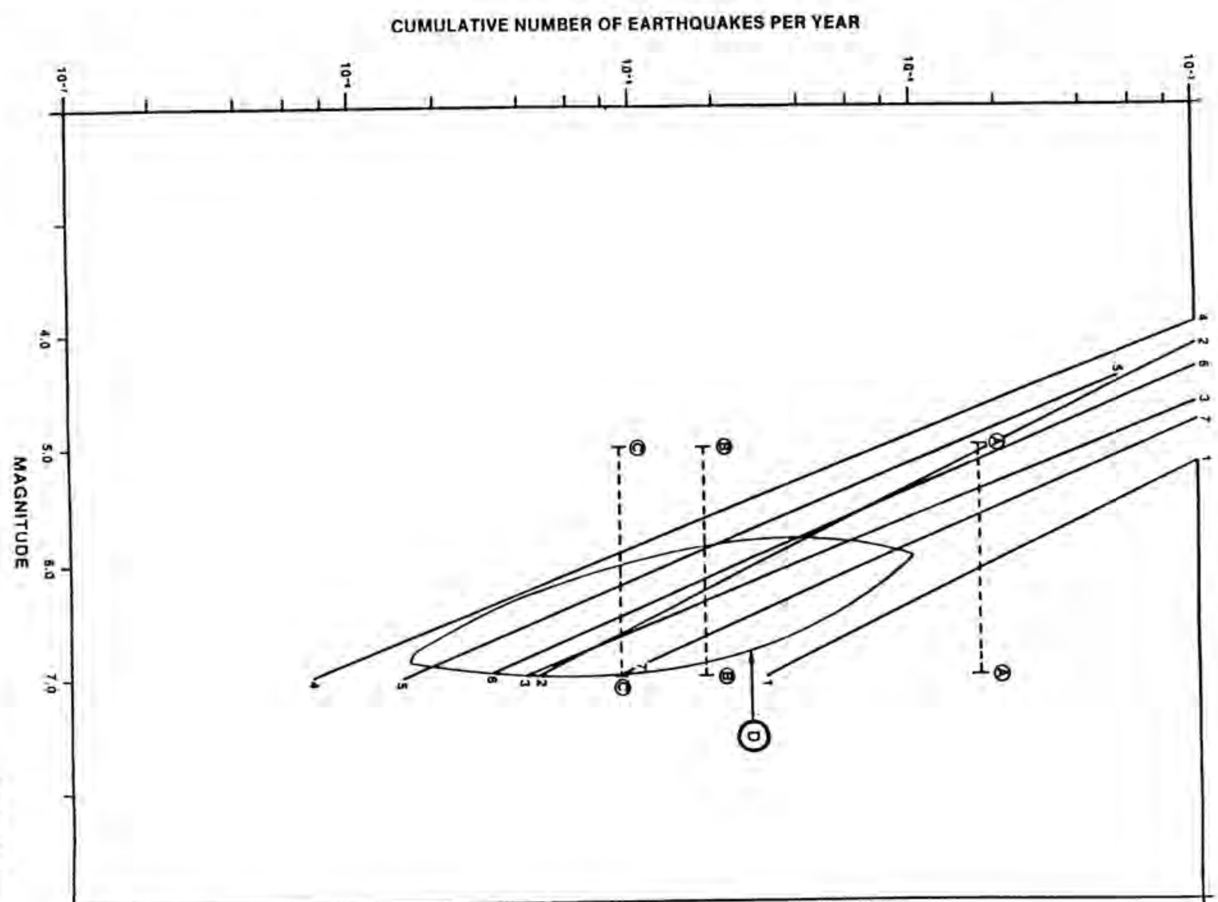

Fig. 1. Plot Showing the Cumulative Number of Earthquakes Per Year Versus Earthquake Magnitude Normalized to an Area of 100 km^2.

quake magnitude normalized to an area of 100 km^2, the maximum size of the controlled area (40 CFR Part 191). The lines labeled 1 to 7 are eathquake recurrence curves for the Great Basin found in the literature and are based on historic and instrumental seismicity, fault patterns, slip rates, and Great Basin strain rates. The specific reference for each curve is listed below Fig. 1.

The horizontal lines labeled A to C are based on the age of last movement for Quaternary faults in the Yucca Mountain region as reported in Environmental Assessment[3] and Whitney 1986[5]. The lines are dashed because the magnitude of potential earthquakes for these faults are not known. The cumulative number of earthquakes was estimated by simply dividing the number of earthquakes was estimated by simply dividing the number of faults by the time period over which these faults have moved, and are also listed below Fig. 1. The elliptical region labeled D is based on estimated slip rates for faults near Yucca Mountain based on geologic trenching studies[5,6], and is drawn to reflect uncertainty based on a limited data base for faults at the site.

Three observations for Fig. 1 are important to note. The first is that different methods appear to give results which are consistent. While too much emphasis should not be placed on the specific numbers for this example, the credibility of specific fault probabilities will be increased if multiple methods give approximately the same answer. The second observation is that there are likely to be large uncertainties for faulting probabilities (factors of 10 to 100) primarily due to the shortness of the historic earthquake record and incomplete geologic data based on recurrent fault movement. As more data is evaluated, these uncertainties can be reduced. Finally, the preliminary probability estimates suggest that fault displacement is credible enough (on the order of 10^{-5} per year) that fault scenarios can not be eliminated based on probability alone. The noncredible probability cutoff for scenarios is described in the 40 CFR Part 191 as being less than a one in ten thousand chance of occurring in 10,000 years.

Magmatic Scenarios

The significance of magmatic scenarios also depends on the way that magmatic events affect the factors significant to repository performance. Table IV lists some example relationships similar to those found in Table II. As shown in Table IV, an extrusive event might exhume a fraction of the waste in the repository during the eruption and entrain the waste in the lava, ash, or gas and thus may discharge radionuclides directly to the accessible environment. Another potential impact is one in which local temperatures are affected by a magmatic intrusion. Local ground water conditions could be altered, and significant geochemical changes could result, thus affecting sorption and solubilities. Increased temperatures could affect the rates of waste-package corrosion, decreasing the waste-package lifetime. Furthermore, the increased local temperatures could cause fracturing in the host rock because of thermomechanical or hydrothermal loading, affecting fluid movement in and around the repository. Geochemical conditions could change if fracturing introduced a new source of ground water into the repository. Magmatic activity could have a less direct impact on the repository as well. For example, extrusive activity away from the site could change the surface-water conditions by damming a nearby river. Such damming could result in large-scale flooding that could affect the site.

The evaluation of magmatic event probabilities is dependent on the last known occurrence of a magmatic event near a site, which may be tens to hundreds of millions years old. One reason this assumption has been made at many sites may be due to the lack of magmatic events during the current tectonic regime. In any case, the evaluation of magmatic scenarios at most locations simply depends on showing that the probability of such an event occurring is acceptably low. As described in 40 CFR Part 191, performance assessments need not consider phenomena if their likelihood is lower than one chance in ten thousand over ten thousand years. At most locations the above criteria can be used to eliminate

TABLE IV

	Examples of How Magmatic Activity Could Affect the Repository-Performance Factors Listed in Table I	Site Conditions and Characteristics Affected from Table I
o	Magmatic activity directly beneath the repository exhumes a portion of the waste packages.	1b
o	Breaching of repository by magmatic activity which, due to thermal conditions, increases flux through repository.	1c 2a
o	Breaching of the repository by magmatic activity causes hydrothermal conditions which shorten containment lifetime due to increased corrosion.	1d
o	Breaching of the repository by magmatic activity which increases dissolution of waste.	3b
o	Breaching of repository by magmatic activity which heats repository area causing changes in host rock mineralogy.	1a 5a-5d
o	Magmatic intrusion which results in thermal or hydrothermal fracturing which creates a new and faster pathway.	4a
o	Magmatic intrusion which results in a modified gradient due to density change.	4c

potential magmatic scenarios. However, for some locations, primarily those with evidence of volcanism during the Quaternary or possibly the late Cenozoic, the probability may be high enough that a magmatic scenario may be credible. The actual probability of occurrence will depend on the history and location of activity, the type of activity and the rate of activity during the current tectonic regime. It is likely that professional judgments may play an important role in applying magmatic probabilities at a specific site.

SUMMARY

In summary, the evaluation of potential tectonic scenarios depends on both the probability of occurrence, and on the way that the tectonic event affects the factors significant to repository performance. While estimates of probability of occurrence are likely to be straightforward, careful thought and analyses are needed to fully evaluate how a given tectonic event can influence hydrologic, geochemical, and mechanical factors important to repository performance. This paper has outlined some of this thought process in detail for potential fault displacement initiating events, and in summary fashion for magmatic initiating events. As site characterization proceeds at each of the candidate repository sites, scenario evaluation will be refined to more adequately evaluate the importance of potential disruptive scenarios.

ACKNOWLEDGEMENT

This work was supported by the United States Department of Energy Office of Civilian Radioactive Waste Management.

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