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DISRUPTION SCENARIOS FOR A HIGH-LEVEL WASTE REPOSITORY AT YUCCA MOUNTAIN, NEVADA

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ABSTRACT

A high-level waste repository located in unsaturated welded tuff at Yucca Mountain, Nevada, would rely on six different, although not entirely independent, barriers to prevent escape of radioactivity. These barriers are the waste canister, fuel cladding, slow dissolution of the spent fuel itself, and slow movement of released contaminants in three different hydrogeologic units: the unsaturated Topopah Spring welded tuff unit, the unsaturated Calico Hills nonwelded tuff unit, and the saturated tuff aquifer. Fifty-eight processes and events that might affect such a repository were reviewed. Eighty-three different sequences were identified by which these processes and events could lead to failure of one or more barriers. Sequences which had similar consequences were grouped, yielding 17 categories. The repository system has considerable redundancy; most of the more likely disruptions affect only one or a few barriers. Occurrence of more than one disruption is needed before such disruptions would cause release of radioactivity. Future studies of repository performance must assess the likelihood and consequences of multiple-disruption scenarios to evaluate how well the repository meets performance standards.

INTRODUCTION

The process of analyzing the long-term safety of a high-level waste repository may be divided conceptually into a series of steps (modified from [1]):

- A comprehensive list of processes and events that could contribute to release of radioactivity from a repository is assembled.
- Processes and events whose occurrence is not credible at the particular site being considered are eliminated.
- Ways in which each process or event could affect the performance of the repository are identified.
- A list of scenarios is selected for further analysis; in each scenario, the events and processes which control repository performance are specified.
- The likelihood of occurrence of each scenario is assessed.
- The consequences to human health if the scenario should occur are calculated.
- The results are evaluated to determine whether the repository is safe.

This paper is directed to the second, third, and fourth of these steps, culminating in identification of scenarios for a high-level nuclear waste repository located in the unsaturated zone at Yucca Mountain, Nevada. The focus is on scenarios involving disruptive events and processes. Only the long-term performance of the repository in containing radioactivity is discussed; operational accidents are not addressed.

Some guidelines are needed to determine which scenarios must be considered. It is assumed here that scenarios whose occurrence in 10,000 yr is highly unlikely (in the sense defined in EPA regulations [2]), or which cannot lead to releases of 100 curies or more of radioactivity within 10,000 yr after repository closure, need not be considered further.

The purpose here is simply to identify the scenarios that require further analysis. A complete analysis of the scenarios is left for the future. Listing of a scenario here does not imply any definite conclusion about its likelihood or consequences; it simply means that information available to the author is insufficient to rule it out.

The preliminary nature of this study requires emphasis. To conceive of everything that might happen in the next 10,000 yr at Yucca Mountain is beyond the imagination of any individual or of any small group of individuals. The list of scenarios to be included in performance assessments of a Yucca Mountain repository must be expanded and refined through the efforts of many individuals over the years of site characterization. Only through wide comment and intense peer review can a reasonably complete list of scenarios be obtained.

BARRIERS TO RELEASE OF RADIOACTIVITY

The potential repository site addressed by this report is at Yucca Mountain, Nevada. It would be located in the unsaturated Topopah Spring Member of the Paintbrush Tuff. A stratigraphic column is provided for reference in Fig. 1. The repository would contain about 70,000 metric tons of spent fuel.

Six different barriers would impede release of radioactivity from such a repository to the human environment. These are canisters in which the spent fuel is packed, fuel cladding, slow dissolution of the waste itself, slow movement downward through the Topopah Spring welded tuff unit in which the repository is located, slow movement downward through the underlying Calico Hills nonwelded tuff unit, and relatively slow lateral movement through the saturated rocks underlying the repository. Many initiating processes and events can affect the performance of more than one barrier. Nevertheless, there is a good deal of

	Stratigraphic Unit	Degree of Welding	Hydrogeologic Unit	Approximate thickness (meters)	Generalized Permeability	
					Matrix	Fracture
	Alluvium	—	Alluvium	0-30	Generally Substantial	—
Paintbrush Tuff	Tiva Canyon Member	Moderate to Dense	Tiva Canyon Welded Unit	0-150	Negligible	Substantial
Paintbrush Tuff	Yucca Mountain Member	Low or None	Paintbrush Nonwelded Unit	20-100	Moderate	Small?
Paintbrush Tuff	Pah Canyon Member					
Paintbrush Tuff	Topopah Spring Member	Moderate to Dense	Topopah Spring Welded Unit	290-360	Negligible	Substantial
	Tuffaceous Beds of Calico Hills	Low or None	Calico Hills Nonwelded Unit (Water Table; Saturated Zone)	100-400	Vitric Tuffs—Substantial; Devitrified Tuffs—Small to Neglible	Small?
Crater Flat Tuff	Prow Pass Member					
Crater Flat Tuff	Bullfrog Member	Undifferentiated	Crater Flat Unit	0-200	Variable	Variable

Fig. 1. Summary of hydrogeologic units above the water table at Yucca Mountain (adapted from [3]).

redundancy in the system; in many scenarios where some barriers fail, other barriers still contain the wastes.

Other barriers would probably be present as well. The most important of these is the capillary barrier created by an air gap (or perhaps some coarse packing material) between the waste packages and the rock. Capillary forces impede the water in the rock matrix, which is under considerable suction, from leaving the matrix, so that an air gap would tend to keep the packages dry. However, the effectiveness of this barrier is at present poorly understood. It may be possible for moisture to wick onto the waste packages at points of contact with the rock, or perhaps to drip on the packages from above. Because of this uncertainty, the scenarios discussed in this paper assume that the capillary barrier is in some way overcome.

Additional geologic units may also serve as barriers; for example, portions of the Crater Flat tuff unit are unsaturated beneath the proposed repository site. With further analysis, such barriers may be incorporated into our understanding of repository performance to provide an additional element of redundancy in the system.

The unfolding of many disruptive scenarios depends on alternative conceptions of the present ground-water flow system in both saturated and unsaturated zones. The "baseline" conceptual model, currently thought to best describe the flow system in the unsaturated zone, is that described by Montazer and Wilson [3]. The baseline conceptual model of the saturated zone is horizontal flow along, roughly, the streamlines calculated by Czarnecki and Waddell [4]. Neither of these conceptual models has been confirmed, and alternatives cannot be ruled out at this time. This study therefore does not assume that the current conceptual models are correct, and addresses scenarios that would be disruptive if reasonable alternative conceptual models turn out to be true. Among the alternative hypotheses that are considered about the present system are

- Flow through the Topopah Spring welded unit, instead of being limited to the rock matrix, goes through fractures.

- Areas of high moisture flux in the deep unsaturated zone are not controlled structurally, as Montazer and Wilson [3] suggest, but by the location of zones of greater infiltration.

- Ground-water velocities in the saturated zone are lower than calculated by Subsection 6.3.1.1.5 of the draft Environmental Assessment of the Yucca Mountain repository site [5]. This might be because the true hydraulic gradient is less than the upper-bound estimate used in the EA or because the regional average hydraulic conductivity is less than measured in well tests because of the presence of flow barriers.

The study was based on a list of relevant phenomena published by a working group of the International Atomic Energy Agency [6]. The likelihood that each of the 57 processes and events on the list will occur at Yucca Mountain was assessed. (One more recently identified initiating process, microbial growth, was also addressed.) For credible events and processes, mechanisms were identified by which the performance of one or more of the barriers to release of radioactivity might be degraded. Some of those mechanisms could be ruled out immediately on the basis of simple physical arguments. The remaining mechanisms were formulated as descriptions of possible future sequences of events. A scenario analyzed in a future performance assessment might involve one of these sequences, or it might involve several occurring at the same time.

Through this analysis, 83 different sequences of disruptive events and processes with the potential of leading to releases of radioactivity were identified. These sequences are described in a detailed report of this work [7]. Each of the 83 sequences involves events and processes proceeding from a single cause. As it is possible that more than one of these causes might operate simultaneously, a very large number of scenarios could be constructed by combining the 83 sequences.

Sequences proceeding from several different causes often lead to very similar results. For example, many sequences lead to a localized zone of higher flux through the Topopah Spring welded unit. The consequences of such sequences are similar, and so they are typically addressed together in performance assessments.

A useful way to organize the discussion of failure sequences is to group them by the barriers they affect. In this way, the redundancies in the system and the degree to which multiple failures are needed to release radioactivity may be seen more easily. In the remainder of this paper, the performance of each barrier under undisturbed conditions and the classes of failure sequences which affect the performance of that barrier will be described.

SATURATED ZONE

In the preliminary performance assessments described in the Environmental Assessment (Subsections 6.3.1.1.5 and 6.4.2.2.2), the saturated zone was found to have rapid ground water flow and to make only a small contribution to performance. Flow times along a 10-km path in the saturated zone, calculated with an effective fracture porosity of 0.002, range from 200 to 2000 yr [8]. However, this conclusion rests on (a) use of a baseline scenario in which all flow in the unsaturated zone is through the rock matrix and (b) pessimistic assumptions about the hydraulic properties of the saturated zone. The argument that ground water is moving much more slowly than assumed by the EA is supported by Claassen's interpretation of the geochemical data [9], suggesting that water has moved little since recharge events 10,000 yr ago.

Furthermore, the matrix porosity of the saturated units is much larger than their fracture porosity, so matrix diffusion can be expected to introduce an additional delay not included in the ground-water travel times. The delay factor of 100 suggested by Sinnock et al. [8] is a reasonable upper bound on the effect of matrix diffusion, as the delay factor cannot exceed the ratio of total to fracture porosity. A delay approaching this magnitude would cause travel times to exceed 10,000 yr, even with the most pessimistic estimates of water velocities.

Also, sorption will significantly delay most species in this zone.

These considerations suggest that after site characterization, the saturated zone could be found to act as a significant barrier to radionuclide migration. Delay times might be sufficient that the repository would still perform acceptably in the event of rapid fracture flow through the unsaturated zone. Scenarios involving degraded performance of the saturated-zone flow system therefore ought to be considered here.

Five sequences (three sequences in which the water table rises greatly and the repository floods and two sequences involving pumping) lead to creation of new ground-water discharge points closer to the repository. Such an event might reduce the distance to the accessible environment by a factor of 2, 3, or more and would correspondingly reduce the travel time through the saturated zone.

A variety of sequences (nine which do not cause the water table to rise significantly, three which do cause the water table to rise, and the flooding sequences mentioned in the previous paragraph) lead to faster flow in the saturated system, usually because of increased hydraulic gradients. Properties of the saturated flow system which might cause it to have slow flow have not yet been defined, and specific analyses of these sequences are not possible at this time.

A third group of four sequences involves formation of radioactive colloids (or microbes). Colloidal particles might be retarded by geochemical interactions with rocks much less than dissolved radioactive species are, and their large molecular weight would inhibit matrix diffusion. In this way, formation of colloids could increase migration velocities in all three zones of ground-water movement. If the time required for moisture to move through the unsaturated zone is reduced below 10,000 yr by some other cause, formation of colloids might lead to release of elements present in large quantities (such as plutonium and americium) whose release would otherwise be prevented by chemical retardation and matrix diffusion.

CALICO HILLS NONWELDED TUFF UNIT

Montazer and Wilson [3] identify two principal hydrogeologic units in the volume between the proposed repository level and the water table: the Topopah

Spring welded unit and the Calico Hills nonwelded unit. The properties of these units differ sufficiently that they behave differently in many scenarios, and they are treated separately here.

The lower of the two unsaturated-zone units, the Calico Hills nonwelded unit, has a higher matrix permeability and current information suggests that it lacks continuous fractures. Consequently, fracture flow is less likely to occur in the Calico Hills than in the Topopah Spring unit under both present and possible future conditions, assuming both units remain unsaturated.

The Calico Hills unit has two facies. The repository site is underlain by a low-permeability zeolitic facies. In some locations, this is overlain by a more permeable vitric facies [3]. Because of the greater permeability of the vitric facies, its presence may be ignored for our purposes.

The geometric mean of measured matrix hydraulic conductivities in the zeolitic facies is about 3 mm/yr, with effective porosity at least 1.6% and probably about 23% and saturation about 90% [3]. This implies that flow in the unit is confined to the matrix. Travel times for a thickness of 50 m are computed to range from an expected 100,000 yr for flux of 0.1 mm/yr and effective porosity of 23% to a very conservative 200 yr for flux of 3 mm/yr and effective porosity of 1.6%.

The zeolites of this unit have strongly sorptive properties.

Local alteration of the properties of the Calico Hills unit or of the hydraulic system around it, in six different sequences with causes ranging from climate change and fault movement to temperature-driven geochemical reactions, might lead to fracture flow in localized areas.

The unit would be eliminated altogether as a barrier if the water table were to rise above it. This occurs in three sequences in which the water table does not rise as high as the repository and in the three sequences mentioned previously which involve flooding of the repository.

TOPOPAH SPRING WELDED TUFF UNIT

The minimum thickness of the Topopah Spring welded unit below the level at which the repository will most likely be constructed is slightly less than 50 m. If there is no fracture flow, the unit's moisture content of 10% and flux of 0.5 mm/yr give a water travel time of 10,000 yr. Because the unit has high matrix saturation, water content will vary little with flux, and travel time will be roughly inversely proportional to flux. With a less conservative flux of 0.1 mm/yr, travel time would be 50,000 yr.

Studies to date do not rule out the possibility that fracture flow is occurring in the Topopah Spring under present conditions. Fracture flow would be rapid; Sinnock et al. [8] estimate that for a flux of 4 mm/yr through fractures, the time to travel 50 m would be 10 yr. This implies that for a flux of 0.1 mm/yr through the fractures (in addition to whatever flux is passing through the matrix), the travel time would be between 10 and 400 yr. These estimates are consistent with Thordarson's measurement [10] of 0.8 to 6 yr as the age of water perched in fractures in tuffaceous beds at the wetter Rainier Mesa area.

Even if water flows in fractures, dissolved radionuclides could move more slowly than the water in the fractures because of matrix diffusion. Experimental evidence is lacking on the effectiveness of matrix diffusion in an unsaturated medium. Sinnock et al. [8] estimate that if matrix diffusion operates, unsorbed contaminants should move more slowly than the water in the fractures by a factor of 100 to 400. If this is the case, contaminant travel times will exceed 10,000 yr if the fracture-flow travel time is more than 25 to 100 yr.

The most numerous failure sequences are those which affect the Topopah Spring welded tuff unit. Principal among them are sequences leading to faster movement of ground water through the unit. The increased water velocity could be due to a generalized initiation of fracture flow throughout the unit (eight sequences in which the fracture flow is caused by increased flux and four in which other physical mechanisms operate). It also could reflect creation of a localized zone of higher flux passing through an area where canisters are emplaced (19 sequences, involving such phenomena as formation of perched water tables, erosion of overlying beds which now divert flow laterally, localized infiltration of floodwaters, small changes in stratigraphy due to faulting, construction errors, and future mining).

Fracture flow may already be occurring in the Topopah Spring unit, especially if the percolation rate is higher than the current best estimate. Three sequences assume that such is the case and involve increases in the velocity of water movement in the fractures.

Geochemical retardation in the unit might be reduced, either by formation of colloids (sequences mentioned previously) or by thermal alteration of sorbing minerals. And, of course, if the repository were flooded by a rise in the water table, there would no longer be an unsaturated-zone barrier.

CANISTERS

As long as uniform corrosion is the mode of canister corrosion, the lifetime of the canisters is estimated at 3,000 to 30,000 yr (see Subsection 6.4.2.2.1 of the Environmental Assessment).

The simplest mechanism which would accelerate canister corrosion is an increase in the amount of water flowing past the canisters. This could follow from either a generalized increase in the amount of water percolating through the Topopah Spring unit (eight sequences initiated by climate change, artificial recharge, or the thermal effects of the repository) or any of the sequences involving formation of a localized wet region which are listed in the previous section. The sequences in which the repository is flooded are, of course, extreme examples of this phenomenon. It should be noted, however, that measurements of corrosion rates are based on extensive wetting of the metal [11]. Therefore, greater wetting of canisters than suggested by current hydrologic models would, in itself, probably not cause corrosion to proceed significantly faster than the tests indicate.

A variety of physical and chemical changes in the waste package or its environment could initiate faster localized corrosion mechanisms. These include localized wetting of canisters and mechanical stresses. Accelerated corrosion could also be caused by faulty emplacement or by limitations of canister testing. There are 11 sequences of these types.

Four sequences involve mechanical breakage of canisters.

FUEL CLADDING

More than 99% of the fuel rods to be placed in a repository are clad in Zircaloy; the remainder are clad in stainless steel. Most cladding will be intact at waste emplacement. For boiling water reactors, only between 0.01% and 1% will have failed (Environmental Assessment, Subsection 6.4.2.2.2). Evidence to date indicates that the time to penetration of the remaining rods will be at least 300 yr, and possibly much longer [12]. Some radioactivity is present on the outside of the rods, due in part to activation of crud; cladding will not be a barrier to the release of this contamination.

The EA (Subsection 6.4.2.2.2) explicitly neglects the effect of zirconium fuel cladding in preventing leaching of spent fuel. However, waste packages are being designed to minimize cladding rupture [13], and cladding could well turn out to play a significant role in waste package performance.

In general, sequences involving increased water flux through the repository will accelerate corrosion of cladding as well as canisters. Such sequences are those involving increased percolation through the Topopah Spring unit (described in the preceding section) and three sequences which put increased moisture in contact with the waste package without increasing the flux through the geologic unit. Because corrosion from inside the fuel rods rather than from the outside environment may be the limiting factor in cladding performance, it is not certain whether this would shorten cladding life. Furthermore, the limited data on cladding corrosion are mostly based on complete wetting.

Three sequences, with causes similar to accelerated canister corrosion sequences, accelerate the rate of cladding corrosion. Temperatures over 350 °C can also accelerate cladding failure [12]; two sequences are of this type.

Forces causing mechanical breakage of canisters (sequences listed in the previous section) would probably lead to breakage of cladding as well.

WASTE DISSOLUTION

The significance of waste dissolution rates depends on how they affect releases to the accessible environment. Because sorption reactions will probably prevent release of most waste constituents to the accessible environment within 10,000 yr even in scenarios in which ground water moves enormously faster than expected, the significance of dissolution rates depends on the least retarded species. The total inventory of the unretarded nuclides carbon-14 and iodine-129 is about 7,000 curies at 5,000 yr. (The carbon-14 inventory is somewhat uncertain.) If the waste dissolves at a rate of less than 1 part per million per yr, less than 100 curies of the unretarded species will dissolve within 10,000 yr. The slightly retarded technetium-99 has an inventory of about 900,000 curies, so to prevent dissolution of 100 curies of technetium in 10,000 yr requires an overall dissolution rate below 1 part in 100 million per yr.

Sinnock et al. [8] calculate waste dissolution rates from the equilibrium solubility of uranium. These dissolution rates depend linearly on the moisture flux through the unsaturated zone and the fraction of the water passing through the repository which comes into contact with waste. For a moisture flux of 0.1 mm/yr and 0.25% of the water contacting waste (the expected value for vertically emplaced canisters; horizontal emplacement gives a figure one order of magnitude higher), the waste dissolves at a rate of about 1 part in 100 billion per yr.

If percolation rate is the only parameter changed in these calculations, dissolution of 100 curies of technetium would require a flux of 100 mm/yr for vertical emplacement and 10 mm/yr for horizontal emplacement. Dissolution of 100 curies of iodine and carbon would require a flux of 1,000 to 10,000 mm/yr. Fluxes of 100 mm/yr or more, averaged over the repository area of several square kilometers, are unreasonable even after the most extreme climate changes if the repository remains above the water table.

It should be emphasized that these calculations assume congruent release of all species from the waste. The Swedish KBS study [14] reports that for a "small fraction" of fuel rods, as much as 30% of the iodine can be leached within a few weeks. The total inventory of iodine is 2,310 curies, so nearly 5% of it, would have to leach quickly to exceed 100 curies. Indeed, even release of the entire iodine inventory would not violate the EPA standard. We may assume that KBS's "small fraction" is small enough that the phenomenon may be neglected. If releases as small as 100 curies are of concern, this assumption will have to be confirmed by experiment.

Any of the mechanisms discussed previously which lead to contact of increased amounts of water with the waste package would tend to increase waste dissolution rates. Because performance assessments such as those by Sinnock et al. [8] assume that waste dissolution rates are solubility limited, increases in water flux would change the calculated waste dissolution rates.

Chemical reaction mechanisms might also increase the rate of waste dissolution. Any of the colloid formation mechanisms could have this effect; two other sequences involve additional means of accelerating dissolution.

CONCLUSIONS

Eighty-three different sequences by which one or more barriers could fail have been identified in this study. The sequences are listed in a detailed report [7]. By grouping sequences which have similar consequences, 17 categories were identified. These categories of failures, and the barriers they will affect, are

- direct release - all barriers;
- repository flooding - all barriers;
- colloid formation - waste form and all three hydrogeologic barriers;
- increased water flux through the unsaturated zone - all barriers except the saturated tuffs;
- localized regions of high flux through the repository - all barriers except the saturated tuffs;

- water diverted toward the waste package - waste form, cladding, and canister;
- accelerated dissolution mechanisms - waste form;
- accelerated cladding corrosion mechanisms - cladding;
- accelerated canister corrosion mechanisms - canister;
- canister breakage - cladding and canister;
- fracture flow in the Topopah Spring welded unit without increased moisture flux - Topopah Spring unsaturated tuff;
- reduced sorption in the Topopah Spring welded unit - Topopah Spring unsaturated tuff;
- water table rise above the Calico Hills nonwelded unit - all barriers;
- fracture flow in the Calico Hills nonwelded unit - Calico Hills unsaturated tuff;
- new discharge points - saturated tuffs;
- faster flow in the saturated zone - saturated tuffs; and
- acceleration of pre-existing fracture flow in the Topopah Spring welded unit - Topopah Spring unsaturated tuff.

These categories should form the basis for further work in the analysis of disruptive event and process scenarios.

The amount of redundancy in the Yucca Mountain repository system is notable. Most of the more likely barrier disruption sequences affect only one or a few of the barriers. The sequences in which little redundancy is apparent -- principally direct release, saturation of the Calico Hills unit, and flooding of the repository -- either are very unlikely or require direct human intrusion into the repository. Indeed, further analysis is likely to show most of them to not be credible.

Several general suggestions for the future direction of the Yucca Mountain performance assessment program can be made. These are

- The saturated zone has a considerable potential to provide a redundant barrier if the unsaturated-flow barriers are disrupted. If, as is likely, substantial matrix diffusion occurs, the saturated zone will be quite effective in preventing release of radioactivity within 10,000 yr. Some effort should be devoted to developing a better understanding of the saturated flow system during site characterization and especially to measuring matrix diffusion.
- More needs to be known about whether radioactive colloids will play a substantial role in migration of radioactivity away from a repository. Research on the physics of colloid movement and filtration effects may be more directly useful in bounding the importance of colloids than detailed study of the chemistry of colloid formation.
- Localized corrosion mechanisms are much more likely than uniform corrosion to lead to unacceptable breaches of waste canisters or cladding. Future research should concentrate on these types of corrosion. Especially needed is work on stress-corrosion cracking and on corrosion of partially wetted metal surfaces.
- More work on the corrosion of fuel cladding may show that the cladding is a valuable redundant barrier in the system.
- Research on the chemical properties of the unsaturated zone should concentrate on the case in which water flows through fractures. This emphasis should be retained even if matrix flow is confirmed as the current mechanism of moisture movement, because matrix flow in the Yucca Mountain unsaturated zone is so slow that sorption is not needed to provide acceptable performance unless there is fracture flow.
- More work on the likelihood of certain scenarios would be desirable. The emphasis should be on showing certain low-probability but possibly high-consequence scenarios, such as volcanic eruption and flooding of the repository, to be not credible.

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