WINOGRAD PANEL ON TSPA-VA ~~Blake~~ PS Justus (see summary attached)

VIABILITY ASSESSMENT OF A REPOSITORY AT YUCCA MOUNTAIN

A REPORT TO THE DIRECTOR, U.S. GEOLOGICAL SURVEY

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INTRODUCTION

Yucca Mountain straddles the western boundary of the Nevada Test Site (NTS) in an arid, remote, and thinly populated region of southwestern Nevada. It is a potential site of a monitored geologic repository for the Nation's commercial and military spent nuclear fuel, high-level radioactive waste derived from reprocessing of uranium and plutonium, surplus plutonium, and other nuclear weapons materials. (Collectively, these radioactive materials are known as high-level waste, HLW.) Tens of thousands of metric tons of HLW are presently stored at 78 different locations in 35 states. The fundamental rationale for a geologic repository for these materials is to securely isolate them from the environment and its occupants to the greatest extent possible.

Of interest to the Director will be the knowledge that both the concept of an HLW repository in thick units of unsaturated rock in arid regions and Yucca Mountain as a particularly likely site originated within the Geological Survey, although the idea of underground disposal of HLW dates back to a mid-1950's National Academy of Science forum. In 1976, Director Vincent McKelvey wrote to the U.S. Energy Research and Development Administration (ERDA, the U.S. Department of Energy's (DOE) predecessor) suggesting examination of NTS for HLW disposal sites in view of its remoteness, its long history as a site for underground testing of nuclear weapons, and its thick unsaturated zones containing a variety of rock types. Based on this letter, ERDA and subsequently DOE authorized a search at NTS for disposal sites deep below the water table, the then-favored concept. In the early 1980's when it became apparent that disposal of HLW below the water table at Yucca Mountain was not feasible -- owing to high fracture transmissivity coupled with high ground-water temperature -- Survey scientists suggested to DOE, in oral presentations and in a lengthy memorandum (Messrs. Robertson, Dixon, and Wilson of the Survey to M. Kunich of the DOE, February 5, 1982), that consideration be given to use of the thick unsaturated zone beneath Yucca Mountain as the repository horizon. Detailed generic discussions of such disposal scenarios at the NTS were published by Survey scientists in 1981 and 1983, and the concept was endorsed for further study shortly thereafter by scientists at the Lawrence Berkeley National Laboratory and by the U.S. Nuclear Regulatory Commission.

Thus began the current Yucca Mountain endeavors, with the Survey and the DOE's National Laboratories assigned the task, by the DOE, of characterizing the earth-science aspects of the site. Explicit in the Survey's views on the use of thick unsaturated zones for the disposal of solidified HLW was the assumption of waste retrievability and long-term monitoring. Survey scientists viewed retrievability and monitoring as paramount assets of the unsaturated zone, an environment that appeared to provide a compromise between irretrievable and unmonitorable disposal in deep saturated zones and storage at the surface. Also explicit in the Survey's recommendations was that the repository temperature be kept below 100 ^{o}C, so not to tamper with the natural system in a way that would make its behavior even harder to predict.

In a 1987 amendment to the Nuclear Waste Policy Act of 1982, Congress selected Yucca Mountain, from a group of three sites, for further exploration as the Nation's first HLW repository. The FY1997 Congressional Appropriations Act required the DOE to present to Congress a progress report on its study of Yucca Mountain as a potential repository.

This progress report, entitled "Viability Assessment of a Repository at Yucca Mountain", is to be presented to Congress, the President, and the public in December, 1998. Pending Congressional approval to proceed with Yucca Mountain, the DOE and its contractors plan, between now and 2001, to address important knowledge gaps identified in its Viability Assessment report (hereafter the VA). In the year 2001, according to a schedule presented in the VA, the Secretary of Energy is to decide whether to recommend the site to the President and he, in turn, to Congress. Should all three recommend Yucca Mountain as a HLW repository, the State of Nevada retains the option to serve a notice of disapproval, which may be accepted or overridden by Congress. If these sequential steps lead to the selection of Yucca Mountain as the Nation's first HLW repository, the DOE would then submit a license application to the US Nuclear Regulatory Commission in the year 2002, and, according to the present schedule, begin emplacement of HLW into Yucca Mountain in the year 2010.

The VA is presented in five volumes and an Overview, in aggregate, a few thousand pages of text, tables, figures, and references. These are Volume 1: Executive Summary, Introduction, and Site Description; Volume 2: Preliminary Design Concept for the Repository and Waste Package; Volume 3: Total System Performance Assessment; Volume 4: License Application Plan and Costs; and Volume 5: Costs to Construct and Operate the Repository. The five volumes of VA are in turn supported by voluminous, detailed descriptions of the large number of engineering and scientific analyses undertaken at Yucca Mountain. The supporting document of most interest to earth scientists and to our panel, "Yucca Mountain Site Description", is itself longer than the VA.

The Director will appreciate -- as we hope other readers will -- that our report should be evaluated as whole cloth; individual threads of it need not make sense apart from their fabric. The VA states (Overview, p. 2, Draft C) "The scientific study of Yucca Mountain and the analysis of a preliminary repository design indicate that a repository can be designed and built at the site that would protect public health and the environment for thousands of years. Significant uncertainties, however, do exist about key natural processes, the preliminary design, and how the site and the design would work together". We concur with this general assessment, in terms of what this means in the last months of 1998. At the same time, we believe that the Yucca Mountain site must be continually assessed and reassessed on the basis of a vigorous and comprehensive monitoring program, at least until the decision for closure is made. Later in the report we remind our audience of a truism in the philosophy of science as applied to Yucca Mountain, that absolute viability can never be established for Yucca Mountain--or any other site. But " 70,000 metric tons of HLW has to go somewhere", and it will be the relative viability of various sites that will matter in the end.

ESSENTIALS OF THE VIABILITY ASSESSMENT

The enormously complex political, legal, environmental, scientific, technological, engineering, economic, and public health/safety issues attendant to placing HLW in an underground repository at Yucca Mountain fall into one of three basic categories:

Transporting the waste from the numerous sites where it presently is to the Yucca Mountain site.

Transferring the waste from its existing containers to canisters specifically designed for underground disposal and emplacing them in the repository.

Reckoning the response of the canister-laden, underground repository and the surrounding environment to both internal and external events for the next million years.

The first two of these activities are each daunting engineering enterprises in their own right, and the political, legal, and social issues are no less daunting. They occur in the "pre-closure" period beginning with licensing and lasting 50 to 100 years, possibly several hundred years, whereas the the third involves the repository response in the "post-closure" period of up to a million years. Nevertheless, the first two activities do not concern us here, because they are almost entirely engineering concerns, not earth-sciences concerns, although the design-basis earthquake ground motions for the surface waste handling facilities did, for example, involve significant earth sciences input.

The VA's evaluation of the post-closure repository performance is governed by 1 basic tenet, 4 key attributes, and 19 principal factors (VA, Vol. 3, p. 2-5). The basic tenet is "to contain and isolate the radioactive wastes so that the dose impact to humans is attenuated to a relatively benign level" for periods up to a million years. To realize this tenet, the DOE repository safety strategy is founded on the following four key attributes:

Limited water contacting waste packages

Long waste package lifetime

Low rate of release of radionuclides from breached waste packages

Radionuclide concentration reduction during transport from the waste packages

Associated with these 4 key attributes are 19 principal factors governing the expected post-closure performance of the underground repository at Yucca Mountain, and these may be found in the second column of Table 2.2-2 of VA, Vol. 3, p.2-8, reproduced here as Table 1.[1]

As read from top to bottom in the second column of Table 1, the 19 principal factors outline a sequence of processes, conditions, and events that collectively define the "expected behavior" of the repository system. ("Unexpected behavior" of the repository system is briefly summarized in Appendix I.) This expected behavior of the repository system is calculated for times up to 1 million years into the future. These calculations are described and summarized in the "Total System Performance Assessment" (TSPA) (VA, Vol.3), the heart of the viability assessment. The processes, conditions, and events, together with their attendant uncertainties, expressed by the 19 principal factor are encapsulated in eight conceptual process models that form the basic building blocks of TSPA. These process models are listed in the third column of Table 1. TSPA is mostly a serial calculation, in which results, say, from the Unsaturated Zone Flow Model (which in this case includes precipitation, infiltration, percolation, and seepage), are inputs to the next model, Thermal Hydrology. Feedback loops arise occasionally (the thermal pulse arising from hot canisters will alter the unsaturated zone flow calculations) and are integrated into serial calculations as appropriate. In words, this is what TSPA attempts to quantify:

Climate and climate change in the vicinity of Yucca Mountain determines precipitation on the mountain, some of which infiltrates into it. This

[1] Unless indicated otherwise, table and page numbers cited here and elsewhere are of the July 7,1998 VA draft that we reviewed and may differ from numbers in more recent drafts.

TABLE 1. Framework of the Total System Performance Assessment as summarized in Table 2.2-2 of volume 3 of the Viability Assessment (Draft B)

Table 2.2-2. Principal Sources of Information Used in the Development of the Total System Performance Assessment Model for the Viability Assessment Reference Design

Attributes of the Repository Safety Strategy	Principal Factors	Process Model Abstraction Workshop	Process Model Expert Elicitation	Described in Section
Limited water contacting waste packages	1 Precipitation and infiltration into the mountain	1 Unsaturated Zone Flow Model Abstraction/Testing (M&O, 1997)	Unsaturated Zone Flow Expert Elicitation (M&O, 1997)	3.1
	2 Percolation to depth			
	3 Seepage into drifts			
	4 Effects of heat and excavation on flow			3.2
	5 Dripping onto the waste package	2 Thermal Hydrology Model Abstraction/Testing (M&O, 1997)	Near Field Environment Expert Elicitation (M&O, 1998)	3.2
	6 Humidity and temperature at the waste package			
Long waste package lifetime	7 Chemistry on the waste package	3 Near Field Geochemical Environment Abstraction/Testing (M&O, 1997)		3.3
	8 Integrity of outer waste-package barrier	4 Waste Package Degradation Abstraction/Testing (M&O, 1997)	Waste Package Degradation Expert Elicitation (M&O, 1998)	3.4
	9 Integrity of inner waste-package barrier			
Low rate of release of radionuclides from breached waste packages	10 Seepage into waste package	N/A	N/A	3.5
	11 Integrity of spent fuel cladding	5 Waste Form Degradation and Radionuclide Mobilization Abstraction/Testing (M&O, 1997)	Waste Form Degradation and Radionuclide Mobilization Expert Elicitation (M&O, 1998)	
	12 Dissolution of UO_2 and glass waste forms			
	13 Solubility of neptunium-237			N/A
	14 Formation of radionuclide-bearing colloids			N/A
	15 Transport within and out of the waste package		N/A	
Radionuclide concentration reduction during transport from the waste packages	16 Transport through unsaturated zone	6 Unsaturated Zone Transport Model Abstraction/Testing (M&O, 1997)	N/A	3.6
	17 Transport in saturated zone	7 Saturated Zone Flow & Transport Model Abstraction/Testing (M&O, 1997)	Saturated Zone Flow & Transport Expert Elicitation (M&O, 1998)	3.7
	18 Dilution From Pumping		N/A	
	19 Biosphere Transport	8 Biosphere Model Abstraction/Testing (M&O, 1997)	N/A	3.8

infiltration drives percolation of water in the unsaturated zone, that part of the mountain mass above the water table, to greater depth. If the rate of percolation is sufficiently large at the repository level (approx. 300 m beneath the Yucca Mountain crest), water seeps into the emplacement drifts. This seepage accelerates corrosion of the containment canisters and then the interior cladding about the radioactive wastes, exposing them to the seeping water. This water now becomes the vehicle for dissolving and transporting exposed radionuclides out of the emplacement drifts into the unsaturated zone below and finally to the water table, presently 300 m beneath the repository. Flow in the saturated zone dilutes the concentration of dissolved and colloid-bound radionuclides first reaching the water table, but may allow them access to the biosphere downstream from Yucca Mountain, either by natural processes that bring the contaminated groundwater to the surface or because of human activities, such as groundwater pumping. Radioactive materials emanate harmful radiation, and the "dose rates" of this radiation and, perhaps, the probabilities of exceeding these dose rates must be less than certain amounts at specific distances and times yet to be specified by the Environmental Protection Agency.

That these things happen is not at issue; it is how fast they occur that matters, and this is where the picture gets complicated. How fast does the water move through the unsaturated zone and into the drifts? How fast do the canisters and interior cladding corrode? How quickly are the exposed radionuclides mobilized by the available water? How fast does the now-contaminated groundwater move to the water table below and beyond Yucca Mountain? Numerous existing natural and planned anthropogenic barriers serve to retard the rates of many of these processes; nevertheless, the answers to all of these questions (and many others not articulated here) depend largely, if not entirely on just how much water gets into the mountain, exactly where it goes once it does, how fast it gets to where it is going, and its temperature and chemical composition once it gets there. A staggering amount of engineering and earth sciences knowledge and information (which quite literally runs from abiotic to zeolites) is brought to bear on illuminating the nature and rates, and the causes and effects, of the physical, chemical, thermal, mechanical, corrosive, hydrologic, and geologic processes in play at Yucca Mountain. Nevertheless, scientific uncertainties and differences of opinion among experts remain on most of these matters, and in some cases these uncertainties and differences are considerable.

Despite the noteworthy complexity of the physical system summarized above and the many uncertainties associated with predicting this system's behavior into the future, one issue stands above all others:
How much groundwater seeps into the emplacement drifts?

Seepage into the drifts has two important consequences. First, the presence of water accelerates canister degradation through corrosion, greatly so if it seeps directly on to the canisters. Second, groundwater is the vehicle by which radionuclides exposed by canister degradation are transported to the water table beneath the repository and ultimately to the biosphere.

The significance of this single issue is perhaps best illustrated by another VA table (not reproduced herein; Table 6.1 of Vol. 3, p.6-16), which summarizes the significance of the uncertainty for each of the 19 principal factors for each of three time intervals and a "combined significance." "Seepage into drifts" was the only principal factor to score four "highs" and only one of four principal factors which scored even one "high." According to VA, Vol. 3, p.2-13, "If water is kept away from the wastes [in their underground setting], the wastes pose little or no threat to humans."

COMMENTARY ON THE VIABILITY ASSESSMENT

That seepage into the emplacement drifts is such a critical issue in determining post-closure repository performance is the basis for the commentary in this section. In addition, this issue can and should figure prominently in monitoring strategies for the pre-closure interval and also seems to have figured prominently in the concept and design of several of the engineered barriers. In focusing on this single issue of seepage into the drifts, however, we wish not to leave the impression that there are not many other important issues of concern to the case presented by VA. Space does not permit us to deal with them all, but there are other entities charged with considering VA in its entirety, most notably the U.S. Nuclear Regulatory Commission (NRC) and the Nuclear Waste Technical Review Board. Our commentary here has its origins in three questions: Has seepage into the drifts been credibly estimated? Will seepage into the drifts be monitored in the pre-closure interval? Will it even be possible to monitor seepage in the pre-closure interval?

Briefly, it is our view that VA overestimates percolation rates at the repository horizon and overestimates seepage into the emplacement drifts by an even wider margin. Consequent to these overestimations are various proposed engineering measures to protect against the deleterious effects of seepage. We believe that some of these engineering measures may be unnecessary and others counterproductive with respect to the natural assets of the repository system. In the latter category are concrete liners presently envisioned for the emplacement drifts. These liners will make it impossible to monitor the one process most worth monitoring, namely seepage into the drifts, but others as well, for example, strain/displacement along the joints, fractures, and faults crossed by the drifts.

The case for continued monitoring forms the third part of this commentary, and the conflict between anthropogenic and natural barriers is returned to in the second part. We begin with seepage into the drifts.

Seepage into the Drifts

Seepage into the drifts is primarily controlled by percolation in the unsaturated zone at the repository level, although it also depends on the geometry and spacing of the emplacement drifts. Percolation flux at the repository horizon is equivalent to the net infiltration due to precipitation on the mountain itself, according to the Unsaturated Zone Flow Model Expert Elicitation Project (p.3-22). Net infiltration, however, is a nonlinear function of precipitation, with a greater fraction of precipitation being realized as net infiltration with increasing precipitation. Finally, precipitation depends on climate and climate change. The "finally" of the previous sentence would have it seem to be an afterthought, but it is not: The climate of the future and the precipitation it provides will be the fundamental source driving seepage into the emplacement drifts. It seems to us, then, that climate of the future, specifically future precipitation, is an important, perhaps controlling determinant of the repository system performance at Yucca Mountain.

The VA does not agree. In 1997 and 1998, DOE sponsored eight "model abstraction" workshops and five expert elicitation projects related to the 19 principal factors (Table 1). Not one of these addressed future climate. And, there is surprisingly little in VA with respect to reckoning the uncertainties in either past or future climates. Moreover, "Further studies of past and future climates are not planned." (VA, Vol. 1, p.2-25). The reason for this is that, of the ten key technical issues identified by NRC in 1996 (VA, Vol. 4, p.4-14 to p.4-37), climate of the future emerges only in No. 9,in the form of two of five sub-issues (VA, Vol. 4, p. 4-32). Both of these sub-issues have been "resolved" with NRC.

In fact, an expert elicitation project on future climate at Yucca Mountain was performed by the Center for Nuclear Waste Regulatory Analysis (DeWispelare et al., 1993) under contract to the Nuclear Regulatory Commission, at a time when performance was assessed only out to 10,000 years into the future. Five experts were elicited on six climatic variables, one of which was annual precipitation. Four of the five experts foresaw only modest changes in precipitation over the next 10,000 years, -15 percent to +40 percent. The fifth expert predicted a doubling of precipitation 10,000 years from now.

The VA climate models are constructed from three elements: the dry, present-day climate (P-climate); the long-term average climate (LTA-climate), colder and wetter than the present; and the so-called "super pluvial" climate (SP-climate), wetter and colder still. The P-climate occurs once every 100,000 years, lasts for 10,000 years, and has present-day precipitation (170 mm/yr). The LTA- climate lasts for 80,000 to 90,000 years out of every 100,000 years and has 2x P-climate precipitation. The SP-climate occurs very infrequently, just twice per million years; it lasts for 10,000 years with 3x P-climate precipitation. In the TSPA base-case model, the corresponding infiltration/percolation rates are 8 mm/yr for the P-climate, 42 mm/yr for the LTA-climate, and 110 mm/yr for the SP-climate. [See Figures 4.1-1 and 4.1-2 of VA, Vol. 3).

In the next 10,000 years, the VA's base-case climate model (VA, Vol. 3, Fig. 4.1-1) consists of P-climate for the next 5,000 years and LTA-climate from 5,000 to 10,000 years. This seems to us to be a worst-case model, certainly worse than any that the five experts in the CNWRA/NRC elicitation project proposed. Even in the case of the fifth expert, the integrated rainfall for the next 10,000 years would be only a fraction of that assumed in the VA base-case model. Thus, the VA base-case model results in more seepage in the drifts in the next 10,000 years than is at all likely to occur according to this expert judgment.

For longer time scales, the VA climate scenarios also provide more precipitation than can be found in the geologic record. For example, the penultimate (i.e. the Illinoian stage) glaciation, considered by VA to be a "super-pluvial" event, may never have existed as such in southern Nevada. Briefly, the postulated "super-pluvial" has not left a record of its presence in precipitated secondary minerals found in the mountain (See Appendix II), in shoreline and other geomorphic features within the numerous topographically closed basins of the region, nor in sediments beneath the modern playas. Considered singly, each of these expected, but missing, records might be explained away in one fashion or another. But when considered together, they call into question the occurrence of a "super-pluvial" at Yucca Mountain and adjacent parts of southern Nevada. Indeed, the missing evidence cited above, as well as evidence indicating that the Great Basin has become increasingly arid over the past million years should also alert us to the possibility that even the precipitation doubling postulated for the LTA climate may be an overestimate.

Because the rate of deep percolation at the repository horizon is the most important factor governing the release of radionuclides from the waste packages, numerous hydrologic investigations of the physical, chemical, and isotopic character of the water within Yucca Mountain have been undertaken. Percolation rates in fractured-rock terrains are difficult to quantify, particularly when the rate is no more than, say, 20 mm/yr. A number of techniques have been used to estimate deep percolation rates in Yucca Mountain, resulting in estimates ranging from less than 1 to about 20 mm/yr. However, we note that the VA-assumed present climate rate of 8 mm/yr lasting the 10,000-year duration of the Holocene would result in an 80-m column of water, sufficient to more than replace all of the water in the unsaturated zone at Yucca Mountain. However, some water samples from perched water bodies in the unsaturated zone retain an isotopic signature indicative of Pleistocene recharge. Although this phenomenon might be explained by preferential flow that bypasses much of the unsaturated zone volume, that water should provide a Holocene isotopic signature to water in the saturated zone. In fact, however, water in the saturated zone beneath Yucca Mountain also appears to have a late-Pleistocene isotopic signature. Based on this analysis, it appears that the TSPA base-case estimates of infiltration are too high.

Estimates of other factors governing water movement into the emplacement drifts are even more conservative than the percolation flux estimates. As an example, unsaturated flow into the drifts is assumed to be focused by a mean factor of 5.5 (VA, Vol. 3, p. 4-10, footnote 12). Unsaturated flow theory, on the other hand, indicates that capillary effects tend to keep the seeps within the rock surrounding the emplacement drift, or if seepage into the drift does occur, the water tends to adhere to the rock or drift lining wall, and move down the wall as film flow. In either case, most water would bypass the waste canisters. Such behavior has been confirmed by experiments in the Exploratory Studies Facility (ESF), in which large rates of infiltration have been artificially maintained above an alcove and the water entry into it observed. Both theoretical and experimental results thus indicate that focused flow into drifts is extremely unlikely, and should not be assumed for TSPA. In fact, an assumption of no focusing would be quite conservative, as diversion of flow is the much more likely occurrence.

Thus, a variety of climatologic, geologic, and hydrologic evidence suggest that the VA climate models, associated infiltration/percolation rates, and the VA base-case seepage flow model are overly conservative. Our view is that Yucca Mountain is and will be drier than envisioned by VA and that focused flow of seepage onto canisters is unlikely under any of the purported future climate scenarios. An expert elicitation on the Quaternary paleoclimate and paleohydrology of the southern Great Basin is warranted as a means of addressing these differences of opinion between the VA and our panel.

Natural Assets and Engineered Barriers

To protect against seepage into the emplacement drifts, a variety of engineered barriers are called for in the reference design or as design options. How much engineering is really needed depends on how much water seeps into the drifts, but the extent to which engineered barriers are actually emplaced will be determined by the level of conservatism in estimating that seepage. The primary engineered barrier is the waste package itself, a double-shelled canister featuring both structural strength and corrosion resistance in which the waste rests enmeshed in a highly corrosion-resistant cladding. Our primary concern in this section, however, is the efficacy of just two of these engineered barriers, the concrete drift liners and the "thermal pulse", which results from rapid emplacement of young, hot HLW into the drifts.

The concrete liners apparently have their origin in 10 CFR 60.133(f) which states: "The design of the underground facility shall incorporate excavation methods that will limit the potential for creating a preferential pathway for groundwater to contact the waste packages or radionuclide migration to the accessible environment." To meet this requirement, VA proposes drift excavation with the tunnel boring machine and then "fully lining the drift immediately after excavation" (VA, Vol.2, p. 5-40). This drift liner also serves to protect workers, equipment, and emplaced canisters from premature rockfalls off the drift crown during the pre-closure interval. "A robust lining system of precast concrete segments was selected as the primary ground support system for the emplacement drifts. Other ground support systems may include steel sets with steel lagging in emplacement drifts to be geologically mapped" (VA, Vol.2, p.0-5). Performance confirmation requirements "call for emplacement drifts to be accessible and maintainable for a service life of at least 150 years" (VA, Vol.2, p. 4-30).

VA is aware that the emplacement of close to a million cubic meters of concrete in the form of drift liners permits unknown and potentially adverse chemistry at and near the repository horizon, especially with respect to canister corrosion and mobilization of radionuclides, once exposed. The concrete liners also preclude one of the benefits of natural/artificial ventilation of the drifts, namely the removal of large volumes of water from the host rock of the repository horizon during the pre-closure interval, as will be discussed below. Even more importantly, the concrete liners will make monitoring seepage into the drifts difficult if not impossible and, even if this is not entirely the case, will bias the chemistry of such water samples in unknown and unwanted ways. Accordingly, we strongly recommend steel sets and steel lagging as the primary ground support system.

The HLW to be emplaced in Yucca Mountain, produces heat as it decays, and this heat will impress a thermal load upon the repository system. Because this thermal loading can have a wide range of effects -- some purportedly beneficial and others potentially adverse -- considerable discussion has occurred over the past decade as to whether the repository temperatures should be allowed to exceed 100 ^{o}C. A long list of potentially adverse effects is presented in Vol. 1, Draft B, p. 2-6 of VA. "The heat generated by the waste could affect the geohydrologic regime in the near field by causing boiling conditions for hundreds to thousands of years. This could temporarily produce zones of dried-out rock, zones in which condensation would occur, and zones with relatively low humidity. These effects would probably influence the amount of liquid water contacting waste (as a function of time after emplacement). Geochemical processes affected by the heat could include mineral dehydration, dissolution and precipitation of minerals, and change in local water chemistry. Geologic testing shows that thermal loading would probably cause the near-field rock to expand and alter the stress on the rock. Increases in compressive stress may induce rockfalls within the drifts and may alter the hydrologic flow system by closing or opening fractures. Temperature increases are also associated with decreases in rock strength." To all of this we can add that the retrieval scenarios spelled out in Vol. 2, p. 4-72 to 4-78 of VA will surely operate more expeditiously if the workers involved experience temperatures of tens of degrees C in the emplacement drifts, not temperatures of hundreds of degrees C. Thus, high thermal loading (i.e., repository temperatures above 100 °C) would seem to be something Yucca Mountain can do without.

Just as importantly, TSPA can also do without the many uncertainties introduced right at the beginning of the calculations by the thermal load. Keeping repository temperatures below 100 °C minimizes these uncertainties, some of which are propagated through the entire 1,000,000-year projections. One of the few things we can control at Yucca Mountain is the magnitude, distribution, and time of emplacement of the thermal load on the repository rocks. Another is ventilation in the mountain, whether it be artificial or natural, to remove heat as well as moisture from the drifts and from the mountain.

Natural circulation of air is known to occur in Yucca Mountain and could be enhanced considerably as a means of ventilation, if a minimal thermal load were harnessed to this goal. While this concept is considered by VA as a design option (Vol. 2, p. 8-16 to 8-18), VA expresses little enthusiasm for it. Enhanced natural ventilation makes use of, and extracts, undesirable heat and also would result in the extraction of large volumes of water from the unsaturated zone. Extraction of water should prolong the period before water comes in contact with the waste canisters.

The concrete drift liners and the thermal pulse, both reference-design, engineered barriers, amount to tampering with the natural barriers in unnecessary, uncertain, and unwanted ways. Our preference is for well ventilated, unlined (but for steel sets and lagging) emplacement drifts, so they may be kept cool and dry.

Safety Strategies and Continued Monitoring

Design margin refers to the margin of conservatism associated with the fabrication and operation of important components in complex engineering projects. Such conservatism is warranted when there is uncertainty in the full range of conditions that these components may experience and in the potential variability of their material properties. Defense-in-depth refers to redundancy or multiplicity of protective and/or operating components, such that the failure of a single component does not by itself lead to system failure. The greater the exposure to loss, the greater one expects the design margins and the deeper the array of defense-in-depth to be.

Continuous monitoring of the operating performance of important components is also a vital safety strategy for complex engineering systems with a high exposure to loss. The idea of continuous monitoring is to make sure that all is well and, if not, to alert the responsible people. Aircraft manufacturers, for example, employ all three strategies -- design margin, defense-in-depth, and monitoring -- in each and every commercial airplane they manufacture, even though they are the beneficiaries of perhaps 50,000 experiments a day in aircraft safety. Problems that have recently surfaced with jet aircraft that have been in commercial service for over two decades should remind us that, even in the case of engineering with a long track record, unanticipated design deficiencies do come to light.

The geologic repository for HLW proposed at Yucca Mountain is an engineering project unique in both the nature of the enterprise and the very long period of time required of the repository-system performance in the post-closure interval. Thus, VA's concern with design margin and defense-in-depth, phrases that arise early and often in VA is certainly appropriate.

Less attention is paid to monitoring repository-system performance. Such monitoring arises principally with respect to "performance confirmation", defined in 10 CFR 60.2 to be " the program of tests, experiments, and analysis which is conducted to evaluate the accuracy and adequacy of the information used to determine with reasonable assurance that the performance objectives for the period after permanent closure will be met" (VA, Vol. 2, p. 4-65). Performance confirmation parameters to be monitored are listed on p. 4-66. One of these is "groundwater flow into the emplacement drifts", which we view as impossible to measure in an unbiased way, once the reference-design concrete liners are in place. Two pages later, VA (Vol. 2, p.4-68) speaks of parameter measurements made in or from performance confirmation drifts, to be situated 15 m above the emplacement drifts. These parameters are listed on p.4-69, and VA acknowledges there that they "do not represent a complete or final list."

We regard continued and continuous monitoring to be both a safety issue and a site credibility issue. A 50-to-100-year record of the physical, chemical, and isotopic character of water seeping into the drifts could do much to increase overall credibility of the site and to support the decision for closure, whenever that is made. We believe that a careful description .

of the proposed monitoring strategy, as well as a detailed and complete list of what is to be monitored--and why, where, how , and for how long -- should be developed expeditiously. The monitoring plan should be based on a process open to the many engineering, earth-sciences, regulatory, and health/safety interests involved with Yucca Mountain.

CREDIBILITY OF THE VIABILITY ASSESSMENT

70,000 metric tons of HLW has to go somewhere, and the essence of the problem of what to do with HLW is just where is it going to go: to outer space, to polar ice sheets, to deep-sea sediments, to Yucca Mountain, or to anywhere else including staying at the many places where it already is? Since 1987, options as to place have been greatly reduced: existing HLW goes to Yucca Mountain or it stays where it is (default option), pending passage of Congressional bills calling for interim surface storage near Yucca Mountain or elsewhere.

Apart from the choice of place, there are two options of strategy involved in the disposition of HLW. One is waste storage at the surface: the idea behind this strategy is that the HLW is monitorable, accessible, retrievable, and potentially reusable. The other is waste disposal underground: in this strategy the HLW is inaccessible and non-retrievable, out of sight and out of mind. The storage strategy appeals strongly to those who are concerned that we are neither knowledgeable enough nor wise enough to make the final disposal decision. Monitoring activities and retrievability plans, however, can be maintained only at some cost. But it is the accessibility to human intrusion that is the principal concern about long-term surface storage, especially in the event that institutional control of the storage site(s) is lost. The pros and cons of the underground disposal strategy are pretty much the converse of the storage strategy, but it is worthwhile being explicit that if anything does go wrong with disposal after it is consummated, it will be difficult if not impossible to fix.

It was recognized nearly two decades ago that the great advantage of Yucca Mountain is that it can be a storage site as long as we want it to be and a disposal site whenever we, or our descendants, choose it to be. While we have not yet found in VA the phrase "monitored, retrievable geologic repository" applied to Yucca Mountain for the pre-closure interval, VA plainly has these features in mind, in its statement of monitoring activities (VA, Vol. 2, p. 4-65 to 4-70) and retrieval scenarios (VA, Vol. 2, p. 4-72 to 4-78). Nevertheless, VA recognizes that much is yet to be decided about the activities in, and duration of, the pre-closure interval. Insofar as this allows monitoring strategies and retrieval scenarios to continue to develop, it is welcome flexibility.

In what follows below, we address several credibility issues associated with VA, and in doing so we will have occasion to distinguish VA credibility from site credibility. This is an important distinction, at least for us. In the end, VA is just a progress report, and no one is proposing it to be a repository for HLW. This belongs to Yucca Mountain, and it is only the site credibility of Yucca Mountain that matters.

To begin, then, readers of VA should understand that it is very much an interim and unfinished document; indeed, it was changing as we read it in the summer of 1998, and changed even more as we wrote this report in the fall of 1998. Matters that were opaque to non-existent in earlier versions of VA are at least in view in later versions of VA. Much work remains to be done as VA metamorphoses into LA (License Application) due in the year 2002. Indeed, Volume 4 of VA is largely devoted to outlining planned additional work in support of LA, and it is easy to imagine that this agenda will be expanded considerably.

A second significant feature of VA--especially for the development of TSPA--is that important rules of the game changed in 1995, when the National Research Council came forth with its report "Technical Bases for Yucca Mountain Standards" (National Academy Press, 1995). Among other things, this report called for the evaluation of the repository-system response and resulting radiation dose rates 1,000,000 years into the future; previously, the operative time scale for TSPA had been 10,000 years. This change in time scale by a factor of 100 put VA, as it materialized just three years later, at a considerable disadvantage, for two reasons. First, the great bulk of site-characterization work at Yucca Mountain was planned and undertaken with the 10,000-year time scale in mind. What happened in and around Yucca Mountain 100,000 years ago or 1,000,000 years ago is much less important for the 10,000-year projection than it is for the 1,000,000-year projection. Second, the many assumptions and educated guesses intrinsic to the TSPA that are plausible and defensible, at least to some extent, for the next 10,000 years will be far less plausible and defensible on the 1,000,000-year time scale. The Geological Survey's first formal statement on the disposition of HLW had the following to say on this matter 20 years ago: "long-term prediction in the biological and earth sciences is unreliable and impossible to perform with high confidence limits because of the great complexity of possible interactions among processes, both identified and unidentified" (Geological Survey Circular 779, p.11, 1978). In short, the 1,000,000-year projections of the TSPA invite almost endless criticism from those who care to provide it as to the validity, sensitivity, and uncertainty of this model assumption or that material parameter. Yet, in both its tone and basic message, VA is plainly optimistic that Yucca Mountain is indeed viable as the site of the nation's first geologic repository for HLW. As we have seen earlier,this conclusion rests upon the quantitative analysis presented in TSPA, an analysis that culminates in radiation dose rates at a point near Yucca Mountain for all times a million years into the future. A third important feature of VA, then, is the implicit sense of absolute viability of Yucca Mountain conveyed by the quantitative ethos of VA. But does absolute viability, with its attendant large uncertainties, of the Yucca Mountain site really make a difference?

unduly optimistic

The VA is aware that no portrayal of absolute viability no matter how rosy, would ever suffice, in and of itself, to certify Yucca Mountain, or any other site, as a HLW repository (Overview, Draft C, p.37). This view would hold even if the many assumptions and large uncertainties associated with the 1,000,000-year projections could be reduced considerably. While such calculations can lead to legitimate assessments of nonviability, and it is of great importance that such an assessment was not the outcome for Yucca Mountain, they can never establish absolute viability of Yucca Mountain. Hence, it will be the viability of Yucca Mountain relative to other options that matters, which means, at the present time, the relative viability of the default option of leaving so much HLW in so many places where it presently is, or HLW placement at a centralized surface storage facility as envisioned in pending Congressional legislation.

DOE has no charge to undertake such relative assessments and VA therefore addresses only Yucca Mountain. Nevertheless, this matter of relative viability does seem to be part of the collective consciousness, however implicitly, of Yucca Mountain matters. The Nuclear Regulatory Commission understands, for example, that proof of suitability for Yucca Mountain will not be forthcoming; "reasonable assurance" is the operative criterion. Congress, in directing DOE in 1987 to consider only Yucca Mountain, presumably had some sense that Yucca Mountain was the best of the three geologic-repository sites under consideration at that time. And it seems to be widely agreed that leaving so much HLW in so many places where it presently is poses greater risks--and a greater range of risks--than does Yucca Mountain, although we are not aware of a quantitative analysis to support this view.

Thus, the empirical and philosophical dilemma posed by the forthcoming EPA standards for Yucca Mountain, that may require projections of radiation doses for up to a million years in the future, is profound. Indeed, requirements for quantitative dose-rate estimates for a million years would appear -- by virtue of probable challenges to the innumerable assumptions embedded in such computations -- to effectively negate storage or disposal of HLW *at any site*, above or below ground. Might this dilemma be mitigated with a more user-friendly, numerically simple, plain-English assessment of Yucca Mountain, one stressing its purported strengths and weaknesses? Such an assessment would be more readily comprehended by the public, legislators, interveners, and lawyers, than the complex TSPA. It could, additionally, permit a comparison of the Yucca Mountain site relative to other proposed HLW storage or disposal plans.

Apart from this matter of relative viability, readers of VA should also take note that the overly conservative approach taken by VA, at least for those aspects of the analysis we have considered here, does not make for an especially credible approach. It is a disappointing turn of events that the "expected behavior" of the repository system, as it materializes quantitatively in TSPA, comes out looking more like worst-case behavior. Quantitative assessments of expected behavior should be just that, what is expected to happen not only on the basis of the eight conceptual process models, but also on the on basis of the likely range of input data and model parameters, whether they be determined from scientific experiment and observation or from elicited expert judgment. A long chain of overly conservative model elements can only lead to correspondingly low probability of occurrence of the resulting repository-system behavior. We have previously seen the climate models, associated infiltration rates, and the seepage flow model as overly conservative, and to this list we can add the saturated-zone transport model, which assumes only minor dilution of radionuclides once they reach the water table, regardless of climate.

All this over-conservatism is not without cost, naturally, and it comes in the form of engineered barriers that are correspondingly conservative, so as to protect against overly conservative estimates of seepage into the emplacement drifts. It is in this connection that VA credibility is most readily distinguished from site credibility. Specifically, the concrete drift liners and high thermal load do not seem to us to be reasonable reference-design engineered barriers.

THE IMPORTANCE OF PUBLISHED RESULTS

The Director should know that the bulk of the scientific findings for Yucca Mountain in the past decade have appeared only in the gray literature. We consider it imperative that our scientists, and those of the National Laboratories, the universities, and industry, be given the opportunity to publish their findings in major journals. We urge this for several reasons. First, publication ultimately enhances the findings (and by implications their value to the DOE) by making them available for examination and debate by a wider audience of earth scientists than those closely involved in the Yucca Mountain endeavor. Second, due to extremely tight deadlines, innumerable meetings, and changing priorities, scientists working on the Yucca Mountain Project simply have not had the opportunity to prepare their work for publication, a time-honored scientific obligation. We believe they have earned this right. Third, thick (>150 m) unsaturated zones of the Southwest encompass a minimum volume estimated to be about 22,000 km^3 (M.S. Bedinger, as cited in U.S. Geological Survey Circular 990). The comprehensive studies at Yucca Mountain should serve as the model for future exploration and utilization of this large segment of underground space. But this can occur only if the Survey and other scientists are encouraged to publish their findings. For all these reasons we hope that Survey, DOE, and National Laboratory managers will collectively endorse such efforts.

SUMMARY

The five volume "Viability Assessment of a Repository at Yucca Mountain" and its numerous supporting documents (especially the three volume "Yucca Mountain Site Description ") together comprise a body of earth science information unlikely to be matched, in its comprehensiveness, elsewhere in our country. This voluminous information – collected over a 15-year period by Geological Survey, National Laboratory, university, and industry scientists -- is synthesized in the Total System Performance Assessment volume (Vol.3 of the VA) to produce quantitative estimates of radiation doses to humans residing near Yucca Mountain up to a million years hence. Recognizing the daunting challenge posed by these dose-rate estimates, the VA devotes much of volume 4 ("License Application Plan and Costs") to outlining and then prioritizing work necessary to address the numerous knowledge gaps identified during the TSPA endeavor. In this vein, the following conclusions, prepared for consideration by the Director, may also be of interest to the DOE and its contractors, including our USGS colleagues, as they continue their Yucca Mountain characterization efforts.

1. Our panel is in general agreement with the statement in the VA's Overview (Draft C, p. 2) "The scientific study of Yucca Mountain and the analysis of a preliminary repository design indicate that a repository can be designed and built at the site that would protect public health and the environment for thousands of years". We also agree with the VA that there are still significant concerns that need to be addressed, some of which are listed below.

2. We recognize that TSPA analyses are widely accepted nationally and internationally as the preferred means of evaluating potential sites for HLW disposal. Nevertheless, in view of the enormous technical complexity of the TSPA, and of philosophical questions regarding TSPA-type analyses in general, we believe that a semi-quantitative assessment (i.e., a plain-English description accompanied by simplified calculations) of Yucca Mountain would be a valuable addition. Such an analysis is likely to be more readily comprehended by the public, legislators, interveners, and lawyers than the TSPA. It could also permit a direct comparison of the Yucca Mountain site relative to other proposed HLW storage or disposal plans.

3. The magnitude of seepage into the drifts, under both modern and the past wetter climates of the Pleistocene, is the most important aspect of the TSPA. Given its major importance, and in view of a variety of geologic and geomorphologic evidence suggesting that the VA may have overestimated this seepage, an expert elicitation on Quaternary climate and paleohydrology is needed to encourage further examination and refinement of this key parameter

4. In several places the VA cursorily addresses monitoring during the pre-closure period, even mentioning monitoring up to 300 years, if desired. It is our impression, however, that little substantive thought has been given to monitoring. This impression is underscored by the intent to line the drifts with concrete, a procedure that, if implemented, would preclude measurement of seepage into the drifts, and other important parameters, during the pre-closure period. Design of a substantive monitoring program is needed both to assuage public fears regarding "out of sight, out of mind", and to assure that our descendants will have the proper data to decide if and when to seal the repository.

5. Volume 2 of the VA ("Preliminary Design Concept for the Repository and Waste Package") briefly discusses alternate repository designs. We believe that some of the alternate designs deserve a much closer examination than given them by the VA. For example, the alternate repository design that would use a passive ventilation system -- driven by the HLW-generated heat in conjunction with the high fracture transmissivity of the Tiva and Topopah Spring Formations -- appears noteworthy for pre-and-post closure removal of both moisture and heat. And, it will come as no surprise -- given past published USGS statements

on this subject – that we have reservations about a high heat load repository. We favor keeping repository temperatures below 100 °C in order not to complicate our understanding of an already complex environment. Setting aside a small portion of the repository for monitoring the hydrologic, mineralogic, and structural response of the repository rocks to temperatures above 100 °C might be a prudent experiment.

6. The voluminous knowledge obtained at Yucca Mountain in the past 15 years is of considerable value to the Nation over and beyond Yucca Mountain. We urge the Director and the DOE to ensure that this largely unpublished information – presently available only in DOE "milestone" reports and other gray literature – be published, regardless of the final decision on Yucca Mountain.

ACKNOWLEDGEMENTS

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APPENDIX I "UNEXPECTED BEHAVIOR" OF THE REPOSITORY SYSTEM: DISRUPTIVE EVENTS

"Unexpected behavior" of the repository system refers to the effects on system performance caused by infrequent, unlikely events, specifically volcanism, earthquakes, nuclear criticality, and human intrusion. These matters are discussed in VA, Vol. 3, p.4-41 to p.4-54. The probabilities of occurrence for things like a repository-piercing volcanic eruption, a canister-breaking rockfall induced by earthquake ground motion, and an accidentally accumulated critical pile of exposed radionuclides have been calculated to be very low. Human intrusion scenarios are harder to figure. So long as institutional control of Yucca Mountain is maintained, the chances of inadvertent or malicious intrusion are very small. If institutional control is lost, almost anything could happen, at least in principle, but access to the radioactive waste itself would be impossible in the absence of a substantial logistical and technological infrastructure.

Most Earth scientists will know that Yucca Mountain resides in the Basin and Range Province of the western United States, generally considered to be a region of active tectonics. As such, there has been considerable concern in the Earth Sciences community about the seismic and volcanic hazards to which Yucca Mountain might be exposed. In fact, by the standards of active tectonics, Yucca Mountain and environs has been a surprisingly inactive place, at least over the past half million years or so. Existing geologic, geomorphic, tectonic, paleoseismic and volcanic signatures all point to very low rates of crustal deformation and landform modification in the vicinity of Yucca Mountain, for at least the past half-million years.

In particular, paleoseismic data show that the 10,000-year seismic moment release rate for the faults in and around Yucca Mountain corresponds to one M=6.4 earthquake per 10,000 years, on average. Across the 10-km, east-west spread of the Yucca Mountain faults, this corresponds to an annual extensional strain rate of 10^{-8}/yr, consistent with modern (1983-1993) upper-bound strain rates determined geodetically by Savage et al. (1994).

APPENDIX II . PALEOHYDROLOGIC SIGNIFICANCE OF THE SECONDARY MINERALS IN THE EXPLORATORY STUDIES FACILITY

Observations made in hundreds of open fractures, faults, and other void spaces (the lithophysae) along the 8 km of underground drifts of the Exploratory Studies Facility (ESF), by Zell Peterman and colleagues, have shown the general absence of secondary minerals (chiefly calcite and opal) commonly precipitated by groundwater moving through rhyolitic volcanic rocks. Only a fraction of one percent of these openings have secondary minerals, and commonly, 10 million-year old vapor-phase crystals that grew in the lithophysal voids have no observable secondary coatings. Whether the paucity of these common minerals reflects a paucity of paleo-vadose flow, preferential flow along a fraction of a percent of the open fissures, or the passage of fossil water undersaturated with respect to calcite and opal cannot be determined at this time. What can be said, based on radiometric dating of the calcite and opal deposits (Paces et al., 1996; Whelan et al. 1998), is that: a) there is no indication of an increase in the deposition of these minerals during the last glacial period (the Wisconsinan stage) nor during the one before it (the Illinoian stage), the latter considered to be a "super-pluvial" according to the VA.; b) the secondary minerals were deposited at a steady and extremely slow rate of deposition for millions of years; and c) the presence of these deposits only on fissure footwalls, and in the lower half of lithophysal cavities, provides unequivocal evidence that they are of vadose origin, which, in turn, means that the water table has been below the repository horizon for millions of years.

It is the Panels' opinion that there should be continued study of the secondary calcite and opal deposits in the ESF, as well as in the just completed cross-drift, for clues to the Quaternary and late Tertiary paleohydrology of Yucca Mountain.