Yucca Mountain as a Radioactive Waste Repository

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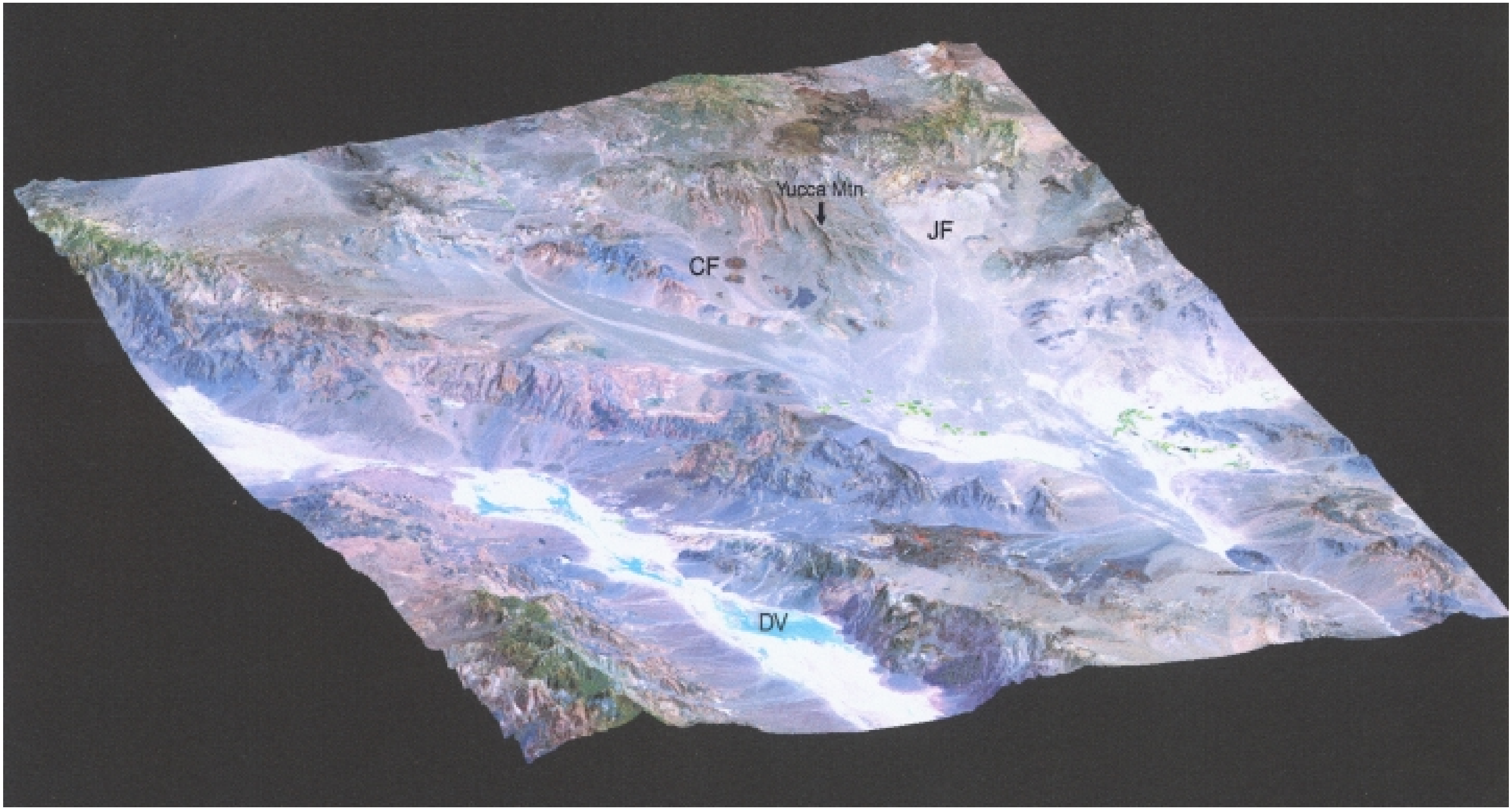
U.S. Department of the Interior
U.S. Geological Survey



Yucca Mountain (arrow) in its regional setting. From lower left to upper right (toward northeast): the Panamint Range, Death Valley (DV, salt pan in blue and white), the Black Mountains and the Funeral Range, the Amargosa Desert traversed by the Amargosa River (sandy-colored dry riverbed trending southeast), Forty-Mile Wash (trending south), and Jackass Flat (JF, sandy-colored area east of Yucca Mountain). Between Yucca Mountain and the Amargosa River lie Crater Flat (CF) with its young volcanic centers (red and black) and Bare Mountain (blue and red). Area of this image and adjacent areas has an interior drainage to Death Valley (elevation, -282 ft), lowest point in the United States. Floodwaters from the Amargosa Desert occasionally reach Death Valley by way of the Amargosa River, which progresses southward off image (lower right) for about 35 mi before turning northward and entering Death Valley (lower left). Ground water enters Death Valley by a more direct route passing under the southern part of the Funeral Range. Image courtesy of K.D. Smith, University of Nevada, Reno.

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FOREWORD

In December 1998, the U.S. Department of Energy released to the public, as mandated by Congress, a five-volume synthesis of its 15 years of study of Yucca Mountain as a potential underground repository for the Nation's spent nuclear fuel and high-level radioactive waste. That document, entitled "Viability Assessment of a Repository at Yucca Mountain," brings together thousands of technical investigations conducted by Federal, State, university, and industry scientists and engineers, including a number of U.S. Geological Survey scientists. It is my belief that the safe disposal of radioactive wastes is one of the great environmental issues of our times. To inform my office about these matters in the specific context of Yucca Mountain, a panel of five senior Survey scientists, chaired by Isaac J. Winograd, was convened to study the Viability Assessment and to identify the central earth-science issues pertaining to Yucca Mountain as a repository for radioactive waste.

Working from earlier drafts of the Viability Assessment, this panel delivered its report to me on November 25, 1998, shortly before the Viability Assessment was officially released. Their report was circulated widely in the technical communities involved with Yucca Mountain and has been generally well received by them, in large part, I believe, because it identifies and addresses major issues in a manner that is direct, brief, and surprisingly readable, given the great complexity of the problem at hand.

To provide this report to a wider audience, we are publishing it as a U.S. Geological Survey Circular, now supplemented by photographs and illustrations. All citizens of our country should know about radioactive-waste-disposal issues in general and Yucca Mountain in particular. They should also know that the choices are not clear cut and that none is without risk, even as all parties concerned, including the U.S. Geological Survey, strive for the optimal solution that will minimize the risk to both present and future generations.

Charles G. Groat
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Yucca Mountain as a Radioactive-Waste Repository

By Thomas C. Hanks, Isaac J. Winograd, R. Ernest Anderson, Thomas E. Reilly, and Edwin P. Weeks

INTRODUCTION

Yucca Mountain straddles the west boundary of the Nevada Test Site in an arid, remote, and thinly populated region of southwestern Nevada. It is the 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] and are to be distinguished from the low-level radioactive waste to be stored at the recently opened Waste Isolation Pilot Plant in southeastern New Mexico.) Tens of thousands of metric tons of HLW is presently stored at more than a hundred sites in 40 States (fig. 1). The fundamental rationale for a geologic repository for radioactive 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 (that is, rock above the water table) in arid regions and the identification of Yucca Mountain as a particularly likely site originated within the U.S. Geological Survey (Winograd, 1974; Roseboom, 1983), although the idea of underground disposal of HLW dates back to a mid-1950's U.S. National Academy of Sciences forum. In 1976, U.S. Geological Survey Director Vincent McKelvey wrote to the

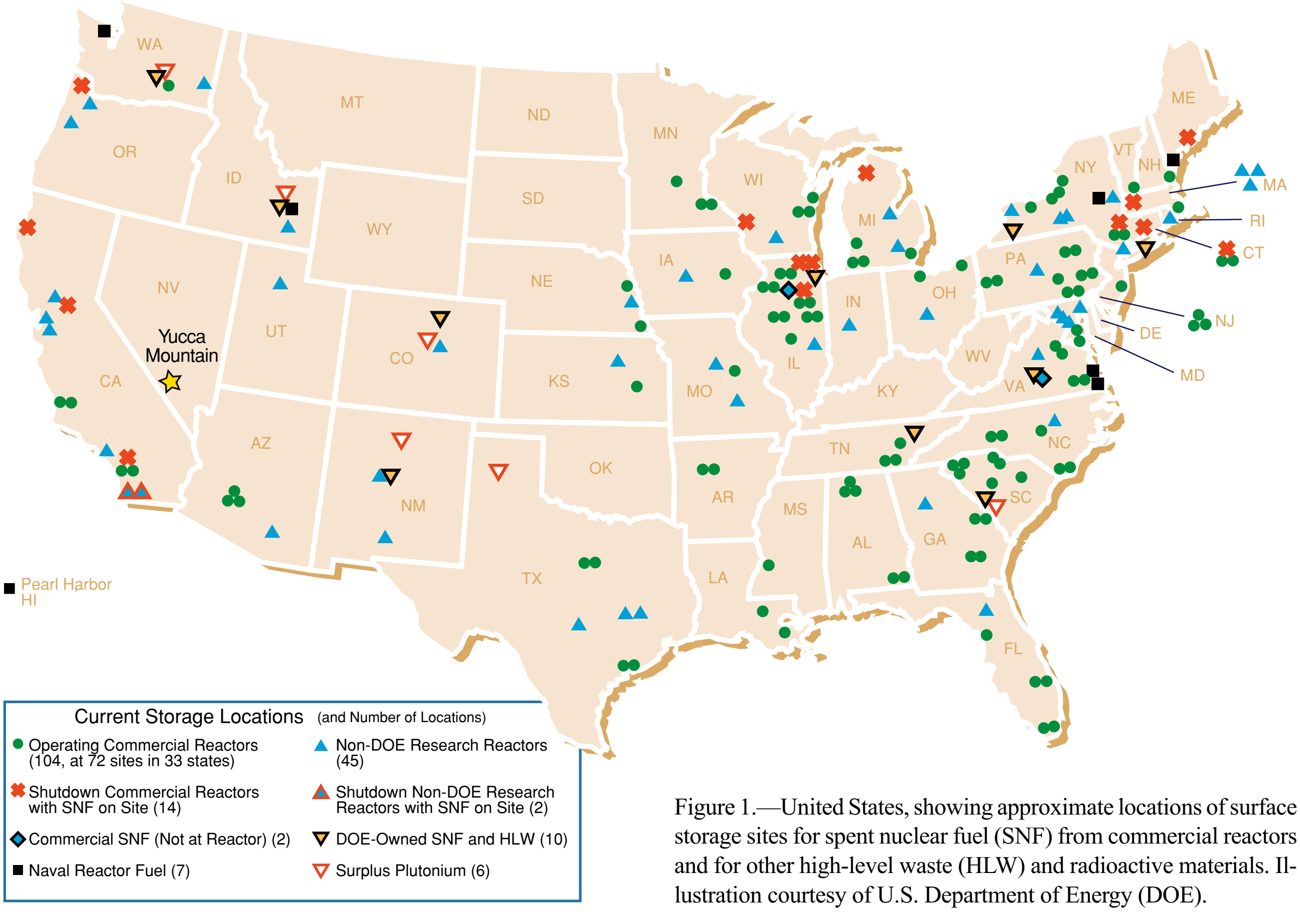

Figure 1.—United States, showing approximate locations of surface storage sites for spent nuclear fuel (SNF) from commercial reactors and for other high-level waste (HLW) and radioactive materials. Illustration courtesy of U.S. Department of Energy (DOE).

U.S. Energy Research and Development Administration (ERDA, the U.S. Department of Energy [DOE]'s predecessor), suggesting examination of the Nevada Test Site 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. On the basis of his letter, ERDA and, subsequently, DOE authorized a search at the Nevada Test Site for HLW-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 DOE, Feb. 5, 1982), that consideration be given to use of the thick unsaturated zone beneath Yucca Mountain as the repository horizon. At the same time, detailed generic discussions of unsaturated-zone storage/disposal scenarios at the Nevada Test Site were published by Survey scientists (Winograd, 1981; Roseboom, 1983), and the concept was endorsed for further study shortly thereafter by scientists at Lawrence Berkeley Laboratory (Wollenberg and others, 1983) and by the U.S. Nuclear Regulatory Commission.

Thus began the current Yucca Mountain endeavors, with the Survey and DOE's national laboratories assigned the task 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 both 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°C, so as 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 potential sites, for further exploration as the Nation's first HLW repository. The Congressional Appropriations Act for Fiscal Year 1997 required DOE to present to Congress a progress report on its study of Yucca Mountain as a potential HLW repository. This progress report, entitled "Viability Assessment of a Repository at Yucca Mountain" (U.S. Department of Energy, 1998a; hereinafter referred to as the Viability Assessment), was presented to Congress, the President, and the public in December 1998. Pending Congressional approval to proceed at Yucca Mountain, DOE and its contractors plan, between now and 2001, to address important knowledge gaps identified in the Viability Assessment. In 2001, according to a schedule presented in the Viability Assessment, the Secretary of Energy is to decide whether to recommend the Yucca Mountain site to the President and he, in turn, to Congress. Should all three recommend the site as an 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, DOE would then submit a license application to the U.S. Nuclear Regulatory Commission in 2002 and, according to the present schedule, begin emplacement of HLW into Yucca Mountain in 2010.

The Viability Assessment is presented in an "Overview" and five volumes, in aggregate about 1,500 pages of text, tables, figures, and references. The five volumes are (1) "Introduction and Site Characteristics," (2) "Preliminary Design Concept for the Repository and Waste Package," (3) "Total System Performance Assessment," (4) "License Application Plan and Costs," and (5) "Costs to Construct and Operate the Repository." These five volumes 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 us, "Yucca Mountain Site Description" (U.S. Department of Energy, 1998b), is itself longer than the Viability Assessment.

The Director will appreciate—as we hope other readers will—that our report should be viewed as whole cloth; individual threads of it need not make sense apart from their fabric. The Viability Assessment states: "Based on the scientific study of Yucca Mountain, DOE believes that the site remains promising for development as a geologic repository. However, uncertainties remain about key natural processes, the preliminary design, and how the site and design would interact" (v. 1, p. 1–1). We concur with this general appraisal, in terms of what it 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 this 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, for that matter, for any other site. But "seventy thousand 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 three basic categories of activities: (1) transporting the waste from the numerous sites where it presently resides to the Yucca Mountain site; (2) transferring the waste from its existing containers to canisters specifically designed for underground disposal and emplacing them in the repository; and (3) 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 categories of activities are each daunting engineering enterprises in their own right, and the political, legal, and social issues are no less fearsome. They occur in the "preclosure" period beginning with licensing and lasting 50 to 100 years (and, possibly, several hundred years), whereas the third category involves the repository response in the "postclosure" period as long as 1 million years. Nevertheless, the first two categories do not concern us here because they are almost entirely engineering concerns, not earth-science concerns, although the estimates of earthquake ground motions to be used for designing the surface waste-handling facilities did, for example, involve significant earth-science input.

The Viability Assessment's evaluation of the postclosure repository performance is governed by 1 basic tenet, 4 key attributes, and 19 principal factors (v. 3, p. 2–4 to 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 as long as a million years. To realize this tenet, DOE's repository-safety strategy is founded on the four key attributes (table 1, col. 1): (1) limited water contacting the waste packages, (2) long waste-package lifetime, (3) low rate of release of radionuclides from breached waste packages, and (4) radionuclide-concentration reduction during transport from the waste packages.

Associated with these four key attributes are 19 principal factors governing the expected postclosure performance of the underground repository at Yucca Mountain (table 1, col. 2).

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 1.) This expected behavior of the repository system is calculated for times as long as 1 million

Table 1.—Framework of the Total System Performance Assessment.

[From Viability Assessment (v. 3, table 2–2)]

Attributes of the Repository Safety Strategy	Principal Factors	Process Model Abstraction Workshop	Process Model Expert Elicitation	Described in Section
Limited water contacting waste packages	Precipitation and infiltration into the mountain	Unsaturated Zone Flow Model Abstraction/Testing (CRWMS M&O 1997t)	Unsaturated Zone Flow Expert Elicitation (CRWMS M&O 1997n)	3.1
	Percolation to depth			
	Seepage into drifts			
	Effects of heat and excavation on flow	Thermal Hydrology Model Abstraction/Testing (CRWMS M&O 1997l)	N/A*	3.2
	Dripping onto the waste package		Near-Field Environment Expert Elicitation (CRWMS M&O 1998d)	3.2
	Humidity and temperature at the waste package			
Long waste package lifetime	Chemistry on the waste package	Near-Field Geochemical Environment Abstraction/Testing (CRWMS M&O 1997d)	N/A*	3.3
	Integrity of outer waste package barrier	Waste Package Degradation Abstraction/Testing (CRWMS M&O 1997h)	Waste Package Degradation Expert Elicitation (CRWMS M&O 1998b)	3.4
	Integrity of inner waste package barrier			
Low rate of release of radionuclides from breached waste packages	Seepage into waste package	Waste Form Degradation and Radionuclide Mobilization Abstraction/Testing (CRWMS M&O 1997o)	N/A*	3.5
	Integrity of spent nuclear fuel cladding		Waste Form Degradation and Radionuclide Mobilization Expert Elicitation (CRWMS M&O 1998k)	
	Dissolution of UO_2 and glass waste forms			
	Solubility of neptunium-237			
	Formation of radionuclide-bearing colloids			
	Transport within and out of the waste package		N/A*	
Radionuclide concentration reduction during transport from the waste packages	Transport through unsaturated zone	Unsaturated Zone Transport Model Abstraction/Testing (CRWMS M&O 1997p)	N/A*	3.6
	Transport in saturated zone	Saturated Zone Flow & Transport Model Abstraction/Testing (CRWMS M&O 1997s)	Saturated Zone Flow & Transport Expert Elicitation (CRWMS M&O 1998g)	3.7
	Dilution from pumping		N/A*	
	Biosphere transport and uptake	Biosphere Model Abstraction/Testing (CRWMS M&O 1997a)	N/A*	3.8

*This principal factor was not the subject of an expert elicitation.

years into the future. These calculations are described and summarized in the "Total System Performance Assessment" (Viability Assessment, v. 3; hereinafter referred to as TSPA), the heart of the Viability Assessment. The processes, conditions, and events, together with their attendant uncertainties, expressed by the 19 principal factors are encapsulated in eight conceptual process models that form the basic building blocks of the TSPA (table 1, col. 3). The 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 the serial calculations as appropriate.

In words, this is what the TSPA sets out to quantify. Climate and climate change in the vicinity of Yucca Mountain determine precipitation on the mountain, some of which infiltrates into it (fig. 2). This 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 high at the repository level (approximately 300 m beneath the Yucca Mountain crest), water seeps into the emplacement drifts (waste-storage tunnels). This seepage accelerates corrosion of the containment canisters and then the interior cladding about the radioactive wastes, exposing them to the seeping water (figs. 2, 3). 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, which is currently 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 ground water to the surface or because of human activities, such as ground-water pumping (fig. 3). 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 certain distances and times yet to be specified by the U.S. Environmental Protection Agency.

That these things happen is not at issue; how fast they occur is what matters, and here things get 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 ground water 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-science 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 so far into the future, one issue stands above all others: How much ground water 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 onto the canisters. Second, water 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 the TSPA's table 6.1, not reproduced here, which summarizes the significance of the uncertainty for each of the 19 principal factors for each of three time intervals (10,000, 100,000, and 1 million years). In that table, "seepage into drifts" was one of only two principal factors (the other being "dilution from pumping") to score four "highs," and one of only five principal factors that scored even one "high." According to the Viability Assessment, "If water is kept away from the wastes, the wastes pose little or no threat to humans" (v. 3, p. 2–15).

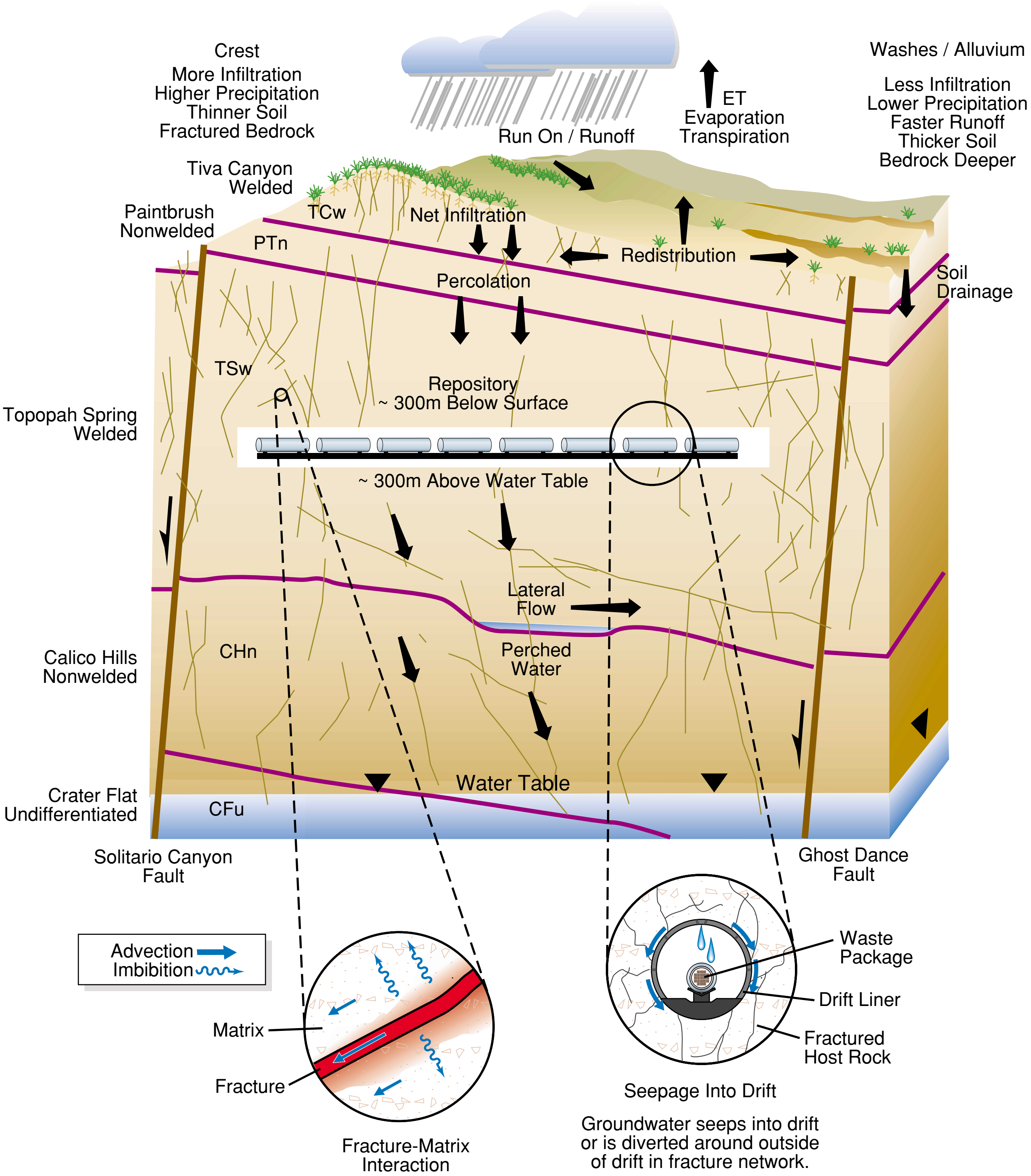

Figure 2.—Block diagram showing stratigraphic and hydrogeologic setting of proposed unsaturated-zone (above water table) repository at Yucca Mountain. From Viability Assessment (v. 3, fig. 3–1).

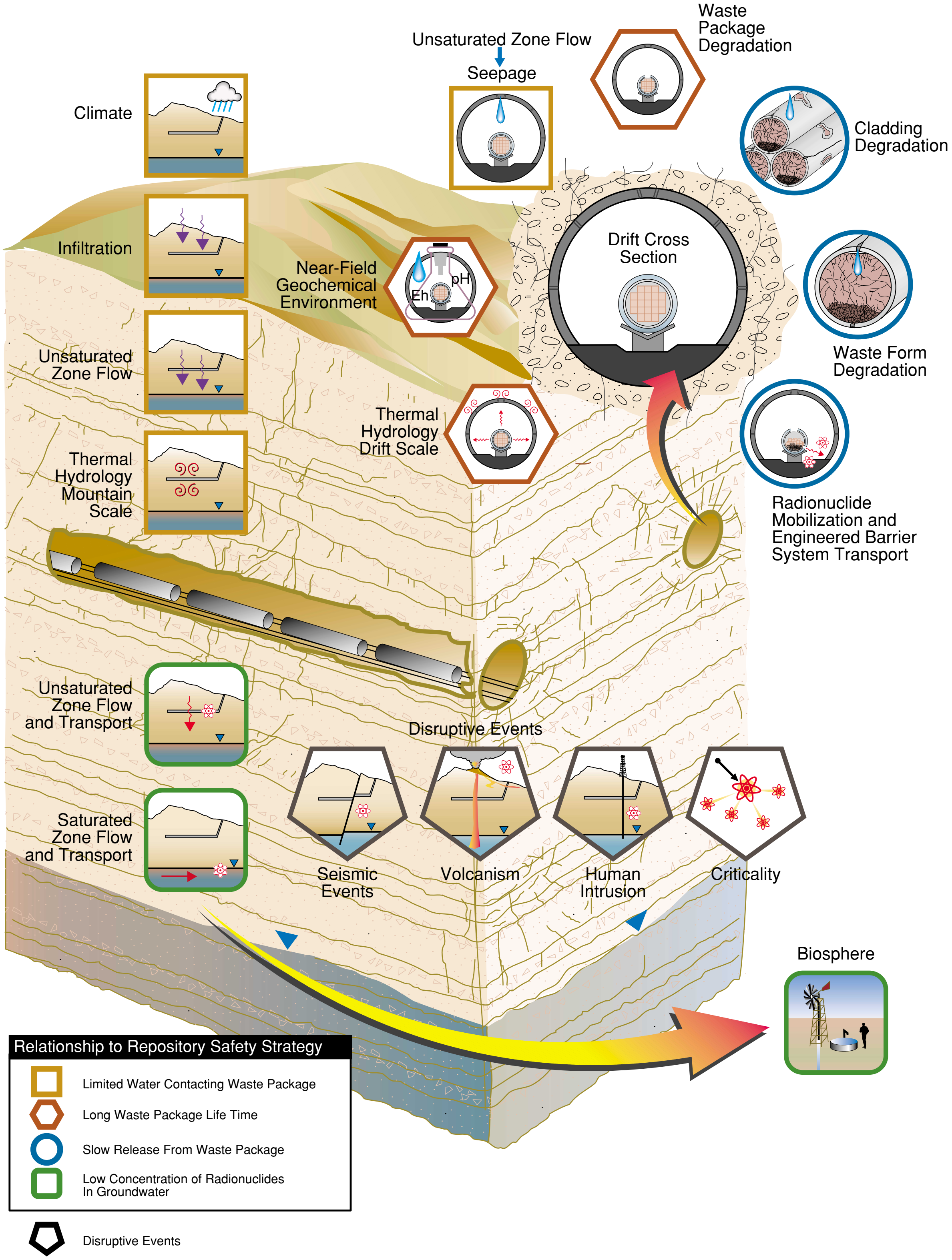

Figure 3.—Block diagram of unsaturated zone (that is, rock between water table and ground surface), highlighting principal expected (see table 1) and unexpected (or “disruptive”; see appendix 1) processes and events that must be analyzed together in an evaluation of Yucca Mountain as a repository for high-level radioactive waste. From Viability Assessment (v. 3, fig. 2–2).

COMMENTARY ON THE VIABILITY ASSESSMENT

That seepage into the emplacement drifts is such a critical issue in determining postclosure 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 preclosure 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, we do not wish to leave the impression that there are not other important issues of concern to the case presented by the Viability Assessment. Space does not permit us to deal with them all, but there are other entities charged with considering the Viability Assessment in its entirety, most notably the U.S. Nuclear Regulatory Commission and the U.S. Nuclear Waste Technical Review Board. Our commentary here has its origins in three questions: (1) Has seepage into the drifts been credibly estimated? (2) will seepage into the drifts be monitored during the preclosure interval? and (3) will it even be possible to monitor seepage during the preclosure interval?

Briefly, it is our view that the Viability Assessment 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 the 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 we return to the conflict between anthropogenic and natural barriers in the second part. We begin with seepage into the drifts.

SEEPAGE INTO THE DRIFTS

Seepage into the drifts is controlled primarily 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. 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 Viability Assessment does not agree. In 1997 and 1998, DOE sponsored eight “model abstraction” workshops and five expert-elicitation projects related to the 19 principal factors governing the “expected” repository-system performance (table 1, cols. 3, 4). Not one of these addressed future climate. The Viability Assessment contains surprisingly little with respect to reckoning the uncertainties in either past or future climates, and “Further studies of past and future climates are not planned” (v. 1, p. 2–35) because, of the 10 key technical issues identified by the U.S. Nuclear Regulatory Commission in 1996 (v. 4, p. 4–10 to p. 4–26), future climate emerges only in No. 9, in the form of two of six subissues (v. 4, p. 4–24). Both of these subissues have been “resolved” with the U.S. Nuclear Regulatory Commission.

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

The Viability Assessment's 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 "superpluvial" 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 about 90,000 years out of every 100,000 years and has twice the P-climate precipitation. The SP-climate occurs rarely, just twice per million years; it lasts for 10,000 years and has three times the P-climate precipitation. In the Viability Assessment's 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 (v. 3, figs. 4–1, 4–2, table 3–5).

For the next 10,000 years, the Viability Assessment's base-case climate model (v. 3, fig. 4–1) consists of P-climate for the next 5,000 years and LTA-climate for the 5,000 years after that. This seems to us to be a worst-case model, certainly worse than any model proposed by the five experts in the aforementioned expert-elicitation project. Even in the case of the fifth expert, the cumulative rainfall for the next 10,000 years would be only a fraction of that assumed in the Viability Assessment's base-case climate model. Thus, this model results in more seepage into the drifts during the next 10,000 years than is at all likely to occur according to this expert judgment.

For longer time scales, the Viability Assessment's climate models also provide more precipitation than can be inferred from the geologic record. For example, the penultimate (Illinoian stage) glaciation, considered to be a "superpluvial" event (U.S. Department of Energy, 1998b, p. 4–39, fig. 4.2–17), may never have occurred in southern Nevada. Briefly, the postulated "superpluvial" event has not left a record of its presence in precipitated secondary minerals found in the mountain (see appendix 2), in shoreline and other geomorphic features within the numerous topographically closed basins of the region, or in sedimentary deposits beneath the modern playas. Considered singly, each of these expected, but missing, records might be explained away in one fashion or another; when considered together, they call into question the occurrence of a "superpluvial" event at Yucca Mountain and in adjacent parts of southern Nevada. Indeed, the missing evidence cited above, as well as evidence indicating that the Great Basin has become increasingly arid during the past million years (Winograd and others, 1985; Winograd and Szabo, 1988; Reheis, 1999), 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 such an important factor governing the release of radionuclides from the waste packages, numerous hydrologic investigations of the physical, chemical, and isotopic characteristics of the water within Yucca Mountain have been undertaken. Percolation rates in fractured-rock terrains are difficult to estimate, particularly when they are no more than 20 mm/yr. Several techniques have been used to estimate rates of deep percolation in Yucca Mountain, with estimates ranging from less than 1 to about 20 mm/yr. We note that the P-climate infiltration/percolation 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 then provide a Holocene isotopic signature to water in the saturated zone. In fact, water in the saturated zone beneath Yucca Mountain also appears to have a late Pleistocene isotopic signature. Thus, the Viability Assessment's base-case estimates of infiltration rates appear to be too high.

Estimates of other factors governing seepage into the emplacement drifts are even more conservative than the percolation-flux estimates. For example, unsaturated flow into the drifts is assumed to be focused by a mean factor of 5.5 (Viability Assessment, v. 3, p. 4–14, footnote 12). Unsaturated-flow theory, however, indicates that capillary effects tend to keep the seeps within the rock surrounding the emplacement drift or, if seepage into the drift does occur, that the water tends to adhere to the rock or drift-lining wall and to 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, in which high 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 in the TSPA. In fact, an assumption of no focusing would be quite conservative because diversion of flow is much more likely.

Thus, various climatologic, geologic, and hydrologic evidence suggests that the Viability Assessment's climate models, associated infiltration/percolation rates, and base-case seepage-flow models are too conservative. Our view is that Yucca Mountain is and will be drier than envisioned by the Viability Assessment 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 us and the Viability Assessment.

NATURAL ASSETS AND ENGINEERED BARRIERS

To protect against seepage into the emplacement drifts, various engineered barriers are called for in the reference design or as design options (fig. 4). 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" that results from rapid emplacement of young, hot HLW into the drifts.

The concrete liners apparently have their origin in Code of Federal Regulations 10 CFR 60.133(f), which states (Viability Assessment, v. 2, p. 5–51): "The design of the underground facility shall incorporate excavation methods that will limit the potential for creating a preferential pathway for ground water to contact the waste packages or radionuclide migration to the accessible environment." To meet this requirement, the Viability Assessment proposes drift excavation with a tunnel-boring machine (see inside back cover) and then "fully lining the drift immediately after excavation" (v. 2, p. 5–51). This drift liner would also serve to protect workers, equipment, and emplaced canisters from premature rockfalls off the drift crown during the preclosure interval. "A robust lining system of precast concrete segments was selected as the primary ground support system for the emplacement drifts. Steel sets with steel lagging will be employed in about 10 percent of the emplacement drifts that are to be geologically mapped" (v. 2, p. 0–4). Performance-confirmation requirements "call for emplacement drifts to be accessible and maintainable for a service life of at least 150 years (v. 2, p. 4–51).

The Viability Assessment is aware that the emplacement of nearly 1 million m^3 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 preclosure interval, as discussed below. Even more importantly, the concrete liners will make monitoring of 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.

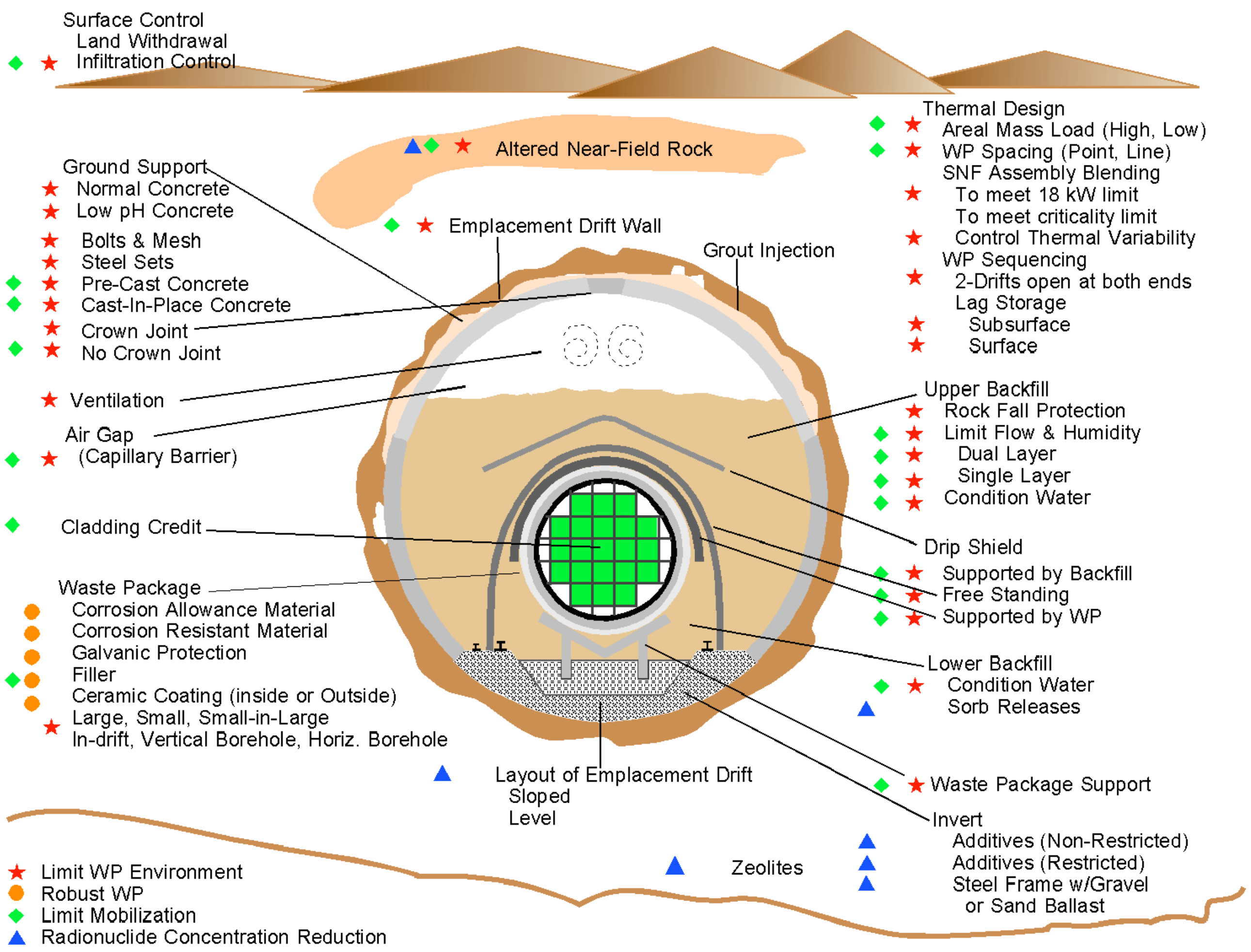

Figure 4.—Design options for engineered barriers considered for emplacement drifts (waste-storage tunnels) at Yucca Mountain (as of Mar. 17, 1999), keyed to four attributes of safety strategy listed on left side of table 1. Purpose of these attributes and function of these engineered barriers are to confine radioactive waste to emplacement drifts for as long as and to the greatest extent possible. Illustration courtesy of U.S. Department of Energy, Yucca Mountain Site Characterization Office, Las Vegas.

Because this thermal loading can have a wide range of effects—some purportedly beneficial and others potentially adverse—considerable discussion has occurred as to whether the repository temperatures should be allowed to exceed 100°C. The Viability Assessment presents a long list of potentially adverse effects (v. 1, p. 2–6):

> 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 the Viability Assessment (v. 2, p. 4–113 to 4–118) will surely operate more expeditiously if the workers involved experience temperatures of tens of degrees Celsius in the emplacement drifts, not temperatures of hundreds of degrees Celsius. Thus, high thermal loading (repository temperatures above 100°C) would seem to be something Yucca Mountain can do without.

Just as importantly, the 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-million-year projections. Some of the few things we can control at Yucca Mountain are 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 within Yucca Mountain and could be enhanced considerably as a means of ventilation, if a minimal thermal load were harnessed to this purpose (Roseboom, 1983; Danko, 1997). Although this concept is considered as a design option (v. 2, p. 8–19 to 8–22), the Viability Assessment expresses little enthusiasm for it. Enhanced natural ventilation would make use of and extract undesirable heat and also would extract 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 (except for steel sets and lagging) emplacement drifts, so that 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 uncertainty exists 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 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 the design margins and the deeper the array of defense-in-depth are expected 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 ensure 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 per day in aircraft safety. Problems that have recently surfaced with commercial jet aircraft that have been in service for more than 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 for repository-system performance during the postclosure interval. Thus, the Viability Assessment's concern with design margin and defense-in-depth, phrases that arise early and often in the report, is certainly appropriate.

Less attention is paid to monitoring repository-system performance. Such monitoring arises principally with respect to "performance confirmation," defined in Code of Federal Regulations 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" (Viability Assessment, v. 2, p. 4–109). Performance-confirmation parameters to be monitored are listed on p. 4–109. One of these is "ground-water 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 (v. 2, p. 4–111), the Viability Assessment speaks of parameter measurements made in or from performance-confirmation drifts, to be situated 15 m above the emplacement drifts. These parameters are listed in table 4–3 of volume 2, but the Viability Assessment acknowledges (v. 2, p. 4–111) 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 characteristics of water seeping into the drifts could do much to support (or question) the overall credibility of the site and to support (or delay) the decision for closure, whenever it 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-science, regulatory, and health/safety interests involved with Yucca Mountain.

CREDIBILITY OF THE VIABILITY ASSESSMENT

Seventy thousand metric tons of HLW has to go somewhere, and the essence of the problem of what to do with HLW is just where it is going to go—to outer space, to polar ice sheets, to deep-sea sediment, 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: Either existing HLW goes to Yucca Mountain, or it stays where it is (default option), pending Congressional actions calling for interim surface storage near Yucca Mountain or elsewhere.

Apart from the choice of place, there are two options of strategy for the disposition of HLW. One is surface storage; this strategy allows the HLW to be monitorable, accessible, retrievable, and potentially reusable. The other strategy is underground disposal in which the HLW is inaccessible and nonretrievable—"out of sight, out of mind." The surface-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 the accessibility to human intrusion 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 those of the surface-storage strategy, but it is worthwhile being explicit that if anything does go wrong after HLW disposal 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 for as long as we want it to be and a disposal site whenever we, or our descendants, choose it to be. Although we have not yet found the phrase "monitored, retrievable geologic repository" applied to Yucca Mountain for the preclosure interval in the Viability Assessment, it plainly has these features in mind, in its statement of monitoring activities (v. 2, p. 4–109 to 4–112) and retrieval scenarios (v. 2, p. 4–113 to 4–118). Nevertheless, the Viability Assessment recognizes that much is yet to be decided about the activities in, and the duration of, the preclosure 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 the Viability Assessment, and in doing so we will distinguish its credibility from site credibility. This is an important distinction, at least for us. In the end, the Viability Assessment 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 the Viability Assessment should understand that it is an interim and unfinished document; indeed, it was changing as we read it in the summer of 1998, and it changed even more as we wrote this report in the fall of 1998. Matters that were opaque to nonexistent in earlier versions of the Viability Assessment are at least in view in later versions. Much work remains to be done as the Viability Assessment metamorphoses into the license application due in 2002. Indeed, volume 4 of the Viability Assessment is largely devoted to outlining planned additional work in support of the license application, and it is easy to imagine that this agenda will be expanded considerably.

A second significant feature of the Viability Assessment—especially for the development of the TSPA—is that important rules of the game changed in 1995, when the National Research Council issued a report entitled "Technical Bases for Yucca Mountain Standards" (National Research Council, 1995). Among other things, this report called for evaluation of the repository-system response and resulting radiation-dose rates 1 million years into the future; previously, the operative time scale for the TSPA had been 10,000 years. This change in time scale by a factor of 100 put the Viability Assessment, as it materialized just 3 years later, at a considerable disadvantage for two reasons. First, most of the 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 or 1 million years ago is much less important for the 10,000-year projection than for the 1-million-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 for the next million years. The U.S. 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" (Bredehoeft and others, 1978). In short, the 1-million-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.

In both its tone and basic message, the Viability Assessment 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 the TSPA, an analysis that culminates in radiation-dose rates at a point near Yucca Mountain for as long as a million years into the future. A third important feature of the Viability Assessment, then, is the implicit sense of absolute viability of Yucca Mountain conveyed by the quantitative ethos of the TSPA. But does absolute viability, with its attendant large uncertainties, of the Yucca Mountain site really make a difference?

The Viability Assessment 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 an HLW repository (Overview, p. 36). This view would hold even if the many assumptions and large uncertainties associated with the 1-million-year projections could be reduced considerably. Although such calculations could lead to legitimate assessments of nonviability—and such an assessment was not the outcome for Yucca Mountain—they can never establish the absolute viability of Yucca Mountain. Thus, it will be the viability of Yucca Mountain relative to other options that matters, which means at present the relative viability of the default option of leaving so much HLW in so many places where it presently is, or its placement at a centralized surface storage facility as envisioned in pending Congressional legislation.

DOE has no charge to undertake such relative assessments, and the Viability Assessment 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 U.S. Nuclear Regulatory Commission understands, for example, that "proof" of the suitability of Yucca Mountain will not be forthcoming; instead, "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 unaware of any quantitative analysis to support this view.

Thus, the empirical and philosophical dilemma posed by the forthcoming U.S. Environmental Protection Agency standards for Yucca Mountain, which may require projections of radiation-dose rates for as long as 1 million years into the future, is profound. Indeed, requirements for quantitative dose-rate estimates for the next million years would appear—by virtue of probable challenges to the innumerable assumptions embedded in such computations—to effectively negate HLW storage or disposal 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 and could, additionally, permit a comparison of the Yucca Mountain site with other proposed HLW storage or disposal sites.

Apart from the matter of relative viability, readers of the Viability Assessment should also take note that its conservative approach, 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 the TSPA, comes out looking more like worst-case behavior. Quantitative assessments of expected repository-system 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 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 conservative model elements can lead only to a correspondingly low probability of occurrence of the resulting repository-system behavior. We have previously viewed the climate models, the associated infiltration rates, and the seepage-flow model as 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 conservatism is not without cost, naturally, and it comes in the form of engineered barriers that are correspondingly conservative, so as to protect against worst-case estimates of seepage into the emplacement drifts. It is in this connection that Viability Assessment credibility is most readily distinguished from site credibility. Specifically, the concrete drift liners and high thermal load do not seem to us to be credible reference-design engineered barriers.

THE IMPORTANCE OF PUBLISHED RESULTS

The Director should know that most of the scientific findings for Yucca Mountain have appeared only in the gray literature.[1] We consider it imperative that Survey scientists, and those of the national laboratories, 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 thus their value to DOE) by making them available for examination and debate by a wider audience of earth scientists than those involved with Yucca Mountain. Second, owing 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 that 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, in Winograd, 1986). The comprehensive studies at Yucca Mountain should serve as a model for future exploration and utilization of this large segment of underground space. But this can occur only if 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 for any other place in our country. This voluminous information—collected over a 15-year period by Survey, national-laboratory, university, and industry scientists—is synthesized in the “Total System Performance Assessment” (TSPA; Viability Assessment, v. 3) to produce quantitative estimates of radiation doses to humans residing near Yucca Mountain for as long as 1 million years into the future. Recognizing the daunting challenge posed by these dose-rate estimates, the Viability Assessment devotes much of volume 4 (“License Application Plan and Costs”) to outlining and then prioritizing the work necessary to address the numerous knowledge gaps identified in the TSPA. In this vein, the following conclusions, prepared for consideration by the Director, may also be of interest to DOE and its contractors, including our Survey colleagues, as they continue their Yucca Mountain site-characterization efforts.

1. We agree with the Viability Assessment’s general appraisal “Based on the scientific study of Yucca Mountain, DOE believes that the site remains promising for development as a geologic repository” (v. 1, p. 1–1). We also agree

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[1] The expression “gray literature” refers to reports that, though peer reviewed and available to the public, have not been published in such technical journals as *Geology*, *Water Resources Research*, *Bulletin of the Geological Society of America*, and so on. By this definition, the Survey’s widely distributed Open-File Reports and Water-Resources Investigations Reports, for example, are gray literature. The chief advantage of gray literature versus publication in journals is the rapidity of release of the information to the public.

with the Viability Assessment's conclusion that significant concerns remain to be addressed, some of which are listed below.

2. We recognize that TSPA-type analyses are widely accepted nationally and internationally as the preferred means of evaluating potential HLW-disposal sites. Nevertheless, in view of the enormous technical complexity of the TSPA and of the philosophical questions regarding TSPA-type analyses in general, we believe that a semiquantitative assessment (that is, a plain-English description accompanied by simplified calculations) of Yucca Mountain would be a valuable addition. Such an analysis will be more readily comprehended by the public, legislators, interveners, and lawyers than the TSPA and permit a comparison of the Yucca Mountain site relative to other proposed HLW storage or disposal sites.
3. The magnitude of seepage into the drifts, under both the present dry climate and the past wetter climates of the Pleistocene, is the most important aspect of the Viability Assessment. In view of its major importance, and in view of various lines of evidence suggesting that this seepage may have been overestimated in the Viability Assessment, 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 Viability Assessment cursorily addresses monitoring during the preclosure period, even for as long as 300 years. 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 preclosure period. Design of a substantive monitoring program is needed both to assuage public fears regarding "out of sight, out of mind" and to ensure that our descendants will have the proper data to decide whether and when to seal the repository.
5. Volume 2 of the Viability Assessment ("Preliminary Design Concept for the Repository and Waste Package") briefly discusses alternative repository designs. We believe that some of these alternative designs deserve much closer examination. For example, the alternative repository design that would use a passive ventilation system—driven by HLW-generated heat in conjunction with the high fracture transmissivity of the Tiva Canyon and Topopah Spring Formations—is noteworthy for preclosure and postclosure removal of both moisture and heat. We also favor keeping repository temperatures below 100°C so as not to complicate our understanding of an already complex environment. Setting aside a small part 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 during the past 15 years is of considerable value to the Nation over and beyond Yucca Mountain. We urge the Director and DOE to ensure that this largely unpublished information—currently available only in DOE "milestone" reports and other gray literature—be published, regardless of the final decision on Yucca Mountain.

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APPENDIX 1. “UNEXPECTED BEHAVIOR” OF THE REPOSITORY SYSTEM: DISRUPTIVE EVENTS

“Unexpected behavior” of the repository system at Yucca Mountain refers to the effects on system performance caused by infrequent, unlikely events, specifically volcanism, earthquakes, nuclear criticality, and human intrusion (Viability Assessment, v. 3, p. 4–80 to p. 4–102). The probabilities of occurrence for things like a repository-piercing volcanic eruption, a canister-breaking rockfall induced by earthquake ground motion, or an accidentally accumulated critical pile of exposed radionuclides have been calculated to be very low. Human-intrusion scenarios are harder to figure, but as long as institutional control of Yucca Mountain is maintained, the chances of inadvertent or malicious intrusion are very small. If institutional control is lost, however, 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-science 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 for the past 500,000 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 during this period.

In particular, paleoseismic data show that the 140,000-year seismic-moment-release rate for the faults in and around Yucca Mountain (Whitney, 1996) corresponds to an average of one M=6.4 earthquake per 10,000 years. Across the 10-km east-west spread of the Yucca Mountain faults, this seismic-moment-release rate corresponds to an annual extensional-strain rate of 10^{-8}/yr, consistent with modern (1983–98) upper-bound strain rates determined geodetically by Savage and others (in press).

APPENDIX 2. PALEOHYDROLOGIC SIGNIFICANCE OF SECONDARY MINERALS IN THE EXPLORATORY STUDIES FACILITY

Inspection of hundreds of open fractures, faults, and other void spaces (lithophysae) along the 8 km of underground drifts at the Exploratory Studies Facility by Zell Peterman and other U.S. Geological Survey scientists have shown the near-absence of secondary minerals (chiefly calcite and opal) commonly precipitated by ground water moving through rhyolitic volcanic rocks. Whether the paucity of these common minerals reflects a paucity of paleovadose flow, preferential flow along relatively few 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, on the basis of radiometric dating of the calcite and opal deposits (Paces and others, 1996; Whelan and others, 1998), is that (1) there is no indication of an increase in the deposition of these minerals during the last glacial period (Wisconsinan stage) or the penultimate glacial period (Illinoian stage), the latter considered to be a “superpluvial” event according to the U.S. Department of Energy (1998b, p. 4–39, fig. 4.2–17); (2) the secondary-mineral coatings indicate an extremely slow, relatively constant rate of deposition for millions of years; and (3) 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.

We recommend continued study of the secondary calcite and opal deposits in the Exploratory Studies Facility, as well as in the just-completed Enhanced Characterization of the Repository Block crossdrift (see back cover, bottom), for clues to the late Tertiary and Quaternary paleohydrology of Yucca Mountain.

FRONT COVER

Yucca Mountain, proposed repository for the Nation's commercial and military high-level radioactive waste. The mountain consists of 11- to 13-million-year-old rhyolitic ash-flow and ash-fall tuffs that have been uplifted and tilted to the east. Surface trace of the Solitario Canyon Fault, a major fault bounding Yucca Mountain, is visible as a faint shadow near base of west (scarp) face of mountain. View south-southeastward; photograph courtesy of U.S. Department of Energy, Yucca Mountain Site Characterization Office, Las Vegas.

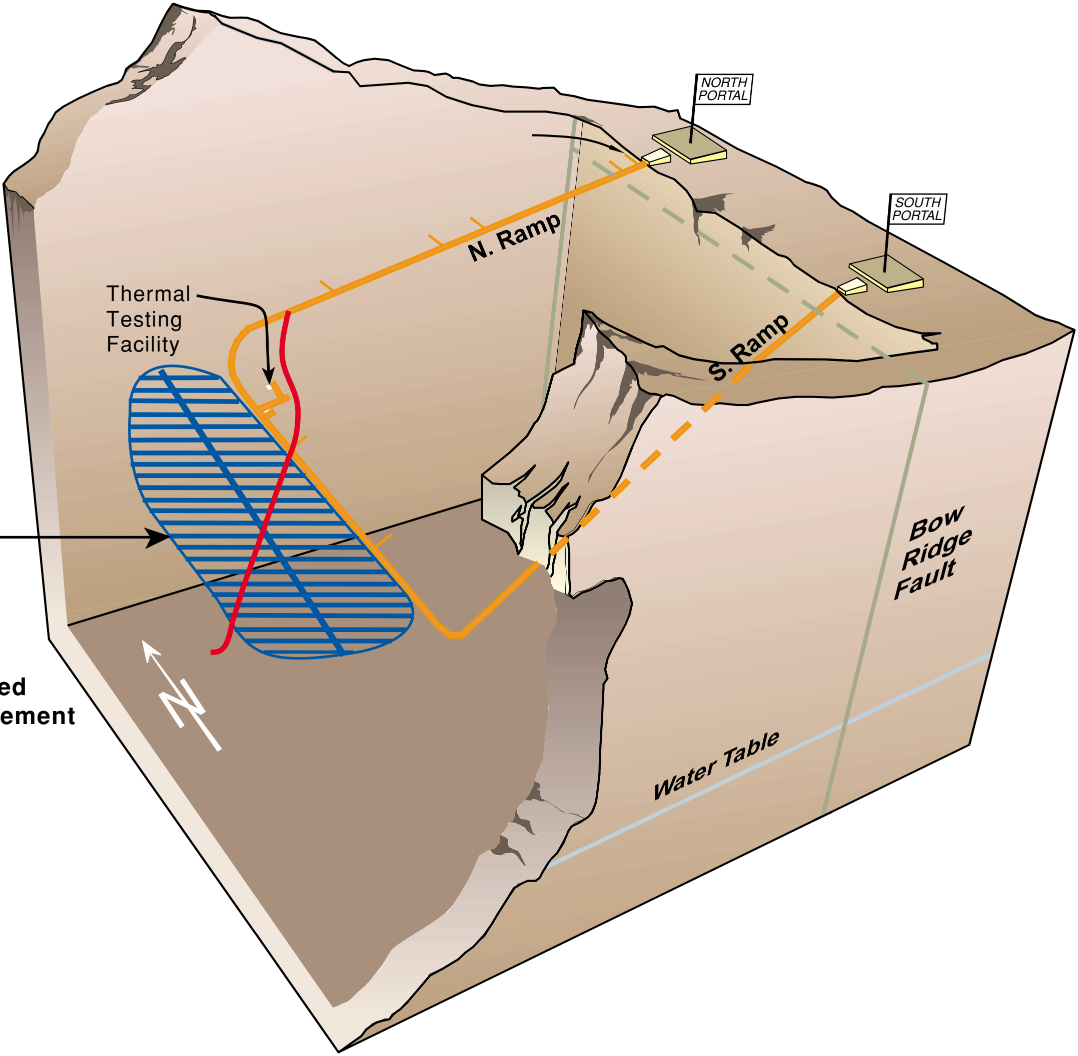
BACK COVER

Top: Yucca Mountain (middle ground). Forty-Mile Wash is in foreground. Pad for the North Portal of Exploratory Studies Facility tunnel (see cutaway view below) is light-colored area at middle right, with the North Portal itself in dark shadow. The South Portal is also visible in dark shadow, near center. At greater distance are Crater Flat with its young volcanic centers, Bare Mountain, the Grapevine Range, and, on skyline, snow-covered crest of the Sierra Nevada. View westward; photograph courtesy of U.S. Department of Energy, Yucca Mountain Site Characterization Office, Las Vegas. **Bottom:** Cutaway view of Yucca Mountain, showing Exploratory Studies Facility tunnel (orange) and Enhanced Characterization of the Repository Block crossdrift (red). Tunnel, which is 8 km long and 8 m in diameter, was begun in September 1994 and completed in April 1997. Crossdrift, which is 2.8 km long and 5.5 m in diameter, was excavated in 1998. Blue grid, schematic view of proposed waste-emplacement drifts at repository horizon. Yucca Mountain crest is approximately 300 m above repository horizon, and water table is approximately 300 m below it. The North and South Portals are also shown in photograph above. Illustration courtesy of U.S. Department of Energy, Yucca Mountain Site Characterization Office, Las Vegas.

INSIDE BACK COVER

Tunnel-boring machine at junction of Exploratory Studies Facility tunnel (North Ramp) and Enhanced Characterization of the Repository Block crossdrift. In comparison with standard drill-and-blast mining techniques, rotary grinding and crushing excavation of tunnel-boring machines minimizes fracturing of rock. Photograph courtesy of U.S. Department of Energy, Yucca Mountain Site Characterization Office, Las Vegas.


AP308
CAUTION



Proposed Emplacement Drifts