Department of Energy
Office of Civilian Radioactive Waste Management
Yucca Mountain Site Characterization Office
P.O. Box 98608
Las Vegas, NV 89193-8608

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Margaret V. Federline, Acting Director
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards
U.S. Nuclear Regulatory Commission
Two White Flint North
Washington, DC 20555-0001

U.S. DEPARTMENT OF ENERGY (DOE) TRANSMITTAL OF INFORMATIONAL COPY: "HIGHLIGHTS OF THE U.S. DEPARTMENT OF ENERGY'S UPDATED WASTE CONTAINMENT AND ISOLATION STRATEGY FOR THE YUCCA MOUNTAIN SITE" (SCPB: N/A)

This letter transmits a courtesy (informational) copy of "Highlights of the U.S. Department of Energy's Updated Waste Containment and Isolation Strategy for the Yucca Mountain Site." The original strategy for waste containment and isolation at the Yucca Mountain, Nevada, site was described in DOE's 1988 Site Characterization Plan. Since that time, much has been learned about the site and the engineered system design has matured. The Updated Waste Containment and Isolation Strategy incorporates recent site characterization information, new repository and waste package designs, more realistic performance predictions, and addresses changing regulatory considerations.

The performance-based understanding of the natural and engineered barriers that is reflected in the updated Waste Containment and Isolation Strategy will guide DOE's plans for a viability assessment in 1998. Assuming the site continues to be viable as a potential repository, DOE will continue to conduct scientific and engineering studies that will aid us in confirming or revising the models that are used to predict performance of the repository system to provide the necessary technical basis for a license application.

Part 1 of the comprehensive "Updated Waste Containment and Isolation Strategy" is being revised by a multi disciplinary author team and will undergo Civilian Radioactive Waste Management System Management and Operating Contractor technical review in early July 1996, and DOE formal review in August. Part 2 will describe the tests being used to address the hypotheses described in part 1, and will be ready for formal review in early fiscal year (FY) 1997. Early revisions of the Strategy were used as input to the Revised Program Plan released in June 1996 and for development of the Project Long-Range Plan and the FY 1997 Annual Plan.

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If you have any questions, please contact Abe Van Luik, Technical Synthesis Team Lead, at (702) 794-1424, or April V. Gil, Licensing Team Lead at (702) 794-5578.

Stephan J. Brocoum,
Assistant Manager for
Suitability and Licensing

AMSL:AVG-2166

Enclosure:
Highlights of the U.S. Department of Energy's
Updated Waste Containment and Isolation
Strategy for the Yucca Mountain Site

cc w/ encl:
L. H. Barrett, DOE/HQ (RW-2) FORS
C. E. Einberg, DOE/HQ (RW-36) FORS
P. A. Bunton, DOE/HQ (RW-36)FORS
A. B. Brownstein, DOE/HQ (RW-36)FORS
R. A. Milner, DOE/HQ (RW-30) FORS
Samuel Rousso, DOE/HQ (RW-40) FORS
S. L. Wastler, NRC, Washington, DC
Paul Pomeroy, ACNW, Washington, DC
W. D. Barnard, NWTRB, Arlington, VA
R. R. Loux, State of Nevada, Carson City, NV
John Meder, State of Nevada, Carson City, NV
Cyril Schank, Churchill County, Fallon, NV
D. A. Bechtel, Clark County, Las Vegas, NV
J. D. Hoffman, Esmeralda County, Goldfield, NV
Eureka County Board of Commissioners, Eureka, NV
B. R. Mettam, Inyo County, Independence, CA
Lander County Board of Commissioners, Battle Mountain, NV
Jason Pitts, Lincoln County, Pioche, NV
V. E. Poe, Mineral County, Hawthorne, NV
L. W. Bradshaw, Nye County, Tonopah, NV
Wayne Cameron, White Pine County, Ely, NV
P. A. Niedzielski-Eichner, Nye County, Chantilly, VA
William Offutt, Nye County, Tonopah, NV

cc w/encl: (cont'd)
R. I. Holden, National Congress of American Indians,
Washington, DC
Tom Burton, Nevada Indian Environmental Coalition,
Reno, NV
R. D. Rogers, PMO, Las Vegas, NV
~~J. D. Rosenthal, PMO, Las Vegas, NV~~
K. M. Cline, PMO, Las Vegas, NV
Nancy Chappell, PMO, Las Vegas, NV
J. L. Younker, M&O, Las Vegas, NV
S. E. LeRoy, M&O, Las Vegas, NV
E. F. O'Neill, M&O, Las Vegas, NV
M. W. Pendleton, M&O, Las Vegas, NV
L. R. Hayes, M&O, Las Vegas, NV
D. F. Fenster, M&O, Vienna, VA
R. P. Gamble, M&O, Vienna, VA
J. R. Dyer, YMSCO, NV
R. V. Barton, YMSCO, NV
A. E. VanLuik, YMSCO, NV
T. W. Bjerstedt, YMSCO, NV
A. V. Gil, YMSCO, NV
C. A. Hanlon, YMSCO, NV
R. G. Hawe, YMSCO, NV
S. B. Jones, YMSCO, NV
D. R. Williams, YMSCO, NV
R. L. Patterson, YMSCO, NV
W. J. Boyle, YMSCO, NV
J. T. Sullivan, YMSCO, NV
R. L. Craun, YMSCO, NV
J. M. Replogle, YMSCO, NV
W. R. Dixon, YMSCO, NV
M. E. Van Der Puy, YMSCO, NV
R. E. Spence, YMQAD, NV
Records Processing Center

HIGHLIGHTS OF THE U.S. DEPARTMENT OF ENERGY'S UPDATED WASTE CONTAINMENT AND ISOLATION STRATEGY FOR THE YUCCA MOUNTAIN SITE

DRAFT

Foreword

This document presents highlights of the U.S. Department of Energy's (DOE) Waste Containment and Isolation Strategy. This draft is in final management concurrence at the Yucca Mountain Site Characterization Office and will be issued as a DOE document. It will be updated as new site, design, and performance information dictate, or when regulatory changes provide impetus for rethinking aspects of the strategy. A more comprehensive version that provides the technical basis for our current understanding of Yucca Mountain, as well as further substantiation of the approaches described in this strategy, is in preparation and should be available in late 1996.

Highlights of the U.S. Department of Energy's Updated Waste Containment and Isolation Strategy for the Yucca Mountain Site

1. INTRODUCTION

The original strategy for waste containment and isolation at the Yucca Mountain site was described in the 1988 Site Characterization Plan (DOE, 1988). Since that time, much has been learned about the site, and the engineered system design has matured, leading to significant improvements in the realism of performance predictions for the combined natural and engineered systems.

Characterization of the site and design of the engineered systems have continued against the backdrop of a changing regulatory framework. The Site Characterization Plan strategy was developed to address the U.S. Nuclear Regulatory Commission's Technical Criteria (10 CFR Part 60) and the standard promulgated by the U.S. Environmental Protection Agency in 1985 (40 CFR Part 191). The 1992 Energy Policy Act directed the Environmental Protection Agency to promulgate a site-specific dose- or risk-based radiation protection standard for Yucca Mountain to replace the release-based standard in Part 191. This standard is currently being drafted.

This strategy incorporates

- recent site characterization information
- new repository and waste package designs
- more realistic performance predictions
- changing regulatory considerations

In this updated strategy, we continue to rely on the attributes of the unsaturated zone environment to provide a setting where waste packages are expected to contain the waste for thousands of years. A schematic of the current concept for the repository is shown in Figure 1. When waste packages are breached and radionuclides are mobilized, the potential for enhanced engineered barriers to prevent or delay transport has become an important consideration. We also continue to rely on multiple natural barriers to limit radionuclide movement and, with the anticipated change to a dose- or risk-based standard, dilution offered by saturated zone flowpaths becomes important. Using this updated strategy, we can focus testing and analysis on those features of the natural and engineered systems that are most important to the safety of the potential repository.

2. FUNDAMENTAL CONCEPTS IN THE UPDATED STRATEGY

This strategy maintains the core of the 1988 Site Characterization Plan strategy: primary protection against corrosion of waste packages and release of radionuclides to the natural system

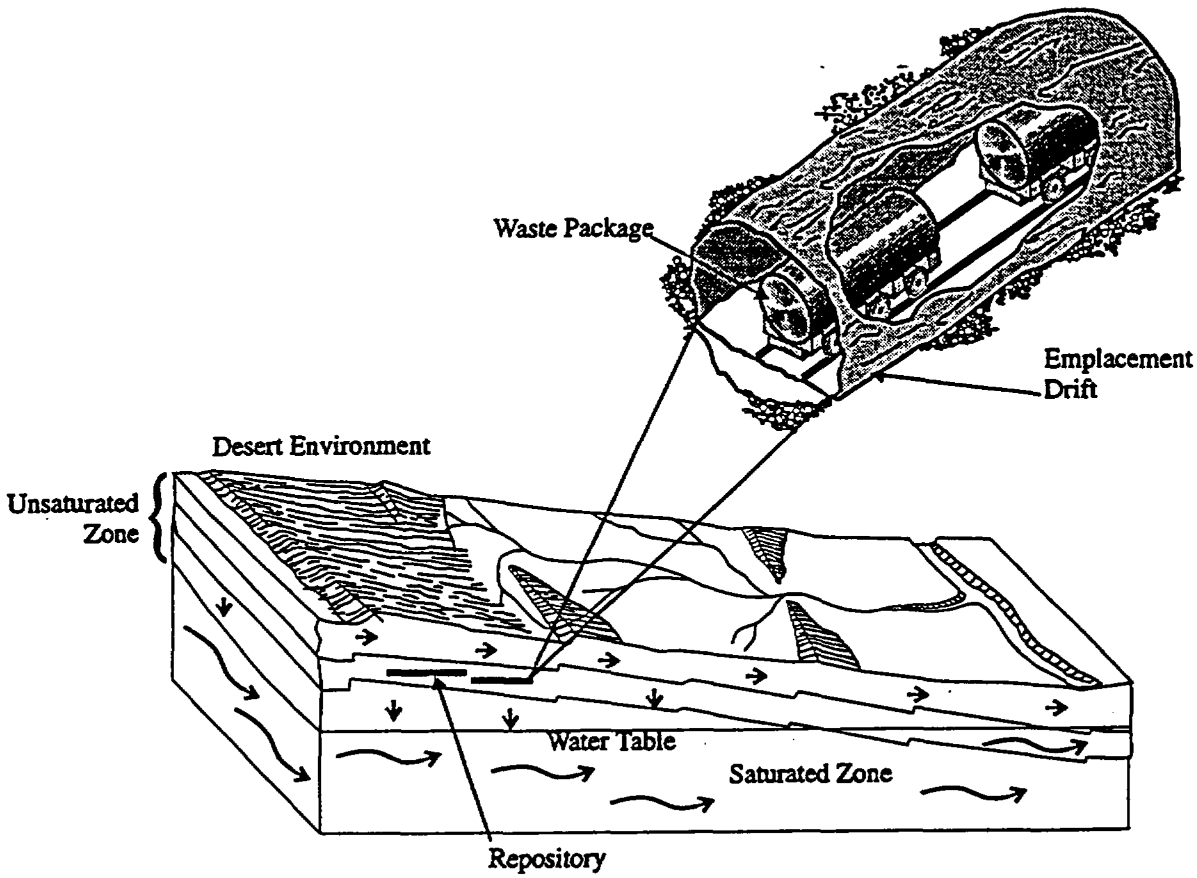

Figure 1. Three-dimensional schematic of repository at Yucca Mountain showing the updated concept with large waste packages that are emplaced in drifts. The unsaturated and saturated zones underlying the repository will provide multiple natural barriers to radionuclide transport.

will be provided by emplacement in the unsaturated zone, more than 200 meters above the water table. The geochemical environment along potential flowpaths in the rock units underlying the repository horizon is expected to provide additional defense by offering considerable sorption of radionuclide species that could eventually be released from the waste packages.

While this strategy retains most of the fundamentals of the original strategy, the current waste package design is more robust, providing additional confidence that waste will be contained for a significant length of time. When radionuclides eventually migrate from the engineered barriers, the strategy continues to rely on the hydrologic and geochemical setting provided by Yucca Mountain to function so that individual exposures are limited to acceptable levels.

The adoption of a risk- or dose-based standard will place additional emphasis on the role of the saturated-zone transport system in decreasing radionuclide concentrations through dilution. The goals of this strategy are to contain the radionuclides within the waste packages for thousands of years, and to ensure annual doses will be acceptably low.

Primary goals of the strategy are

- near-complete containment of radionuclides within waste packages for several thousand years
- acceptably low annual doses to a member of the public living near the site

Increasingly realistic assessments of performance (McGuire et al., 1990; Barnard and Dockery, 1991; Barnard et al., 1992; Eslinger et al., 1993; Wilson et al., 1994; Andrews et al., 1995) help us identify the system attributes that are key to predicting performance of the engineered and natural barriers. Figure 2, modified from Andrews et al. (1995), provides examples of the types of calculations that are available. Calculated radiation doses through time are shown for two different levels of water flow through the unsaturated zone, referred to as high and low infiltration (high corresponds to an average percolation flux of 1.25 mm/yr and low corresponds to an average percolation flux of 0.03 mm/yr). The dose is calculated in millirem/year at a distance of 5 kilometers from the repository. It is expressed as the total peak dose to a person who drinks 2 liters/day of water from the aquifer containing the radionuclides released from the repository. The results are displayed for a 1,000,000-year period, with an expanded view showing the calculated radiation doses for the first 10,000 years. For the low infiltration case, no releases occur over the first 10,000 years and, in fact, the first doses occur after 100,000 years. For the high infiltration case, the first releases occur just prior to 6,000 years in the future. These radiation dose histories are based on a repository with no enhanced engineered barriers and a thermal loading of 83 metric tons of uranium per acre.

From Figure 2, the general observation to be made is that even at the higher infiltration rate, complete containment within the waste package lasts for thousands of years and the peak dose at several hundred thousand years in the future is on the order of the annual dose the average person receives from natural and other radiation sources (about 360 millirem/year). Containment occurs because the waste packages remain intact for a long period, preventing the release of any radionuclides to the surrounding rock. A significant degree of corrosion requires either high humidity or liquid water on the surface of the waste packages. Thus, the rate of ground-water seepage into the potential repository is a major factor for containment. The shape of the dose curve is determined by the chemical and hydrologic factors that affect the rate of release from the engineered barriers and transport through the natural barriers. The annual peak dose depends on the amount of water that can contact the waste in breached waste packages, mobilization rate of radionuclides from the waste form, transport properties of engineered and natural barriers, and dilution provided in the saturated zone.

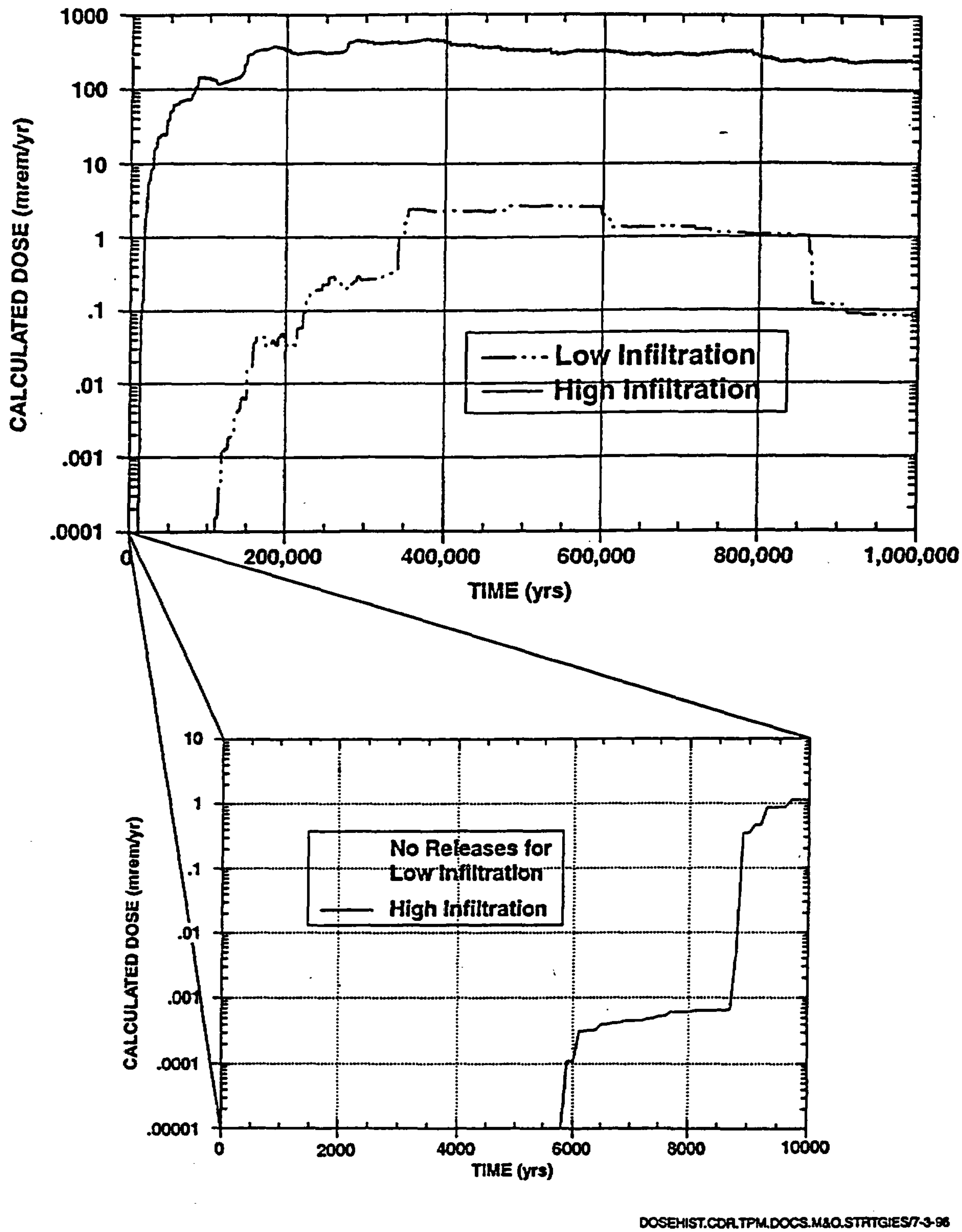

Figure 2. Examples of calculated total dose histories for high and low infiltration cases (modified from Andrews et al., 1995) showing the containment period lasts thousands of years for both high and low infiltration cases. For the high infiltration case, the peak dose at 200,000 years in the future is approximately equal to the annual average radiation dose received from natural and other radiation sources.

The system attributes that have been recognized to be most important for predicting performance of engineered and natural barriers are:

- Rate of water seepage into the repository
- Waste package lifetime (containment)
- Rate of release of radionuclides from breached waste packages
- Radionuclide transport through engineered and natural barriers
- Dilution in the saturated zone below the repository

This performance-based understanding of the natural and engineered barriers will guide our plans for a viability assessment in 1998. Assuming the site continues to be viable as a potential repository, we will continue to conduct scientific and engineering studies, including evaluations of natural analogs. These studies will aid us in confirming or revising the models that are used to predict performance of the repository system to provide the necessary technical basis for a license application.

3. EVALUATING KEY ATTRIBUTES

Defining the key performance attributes of the natural and engineered barriers provides the framework for focusing the testing and analysis program on the most important remaining issues about postclosure safety of the Yucca Mountain site. A number of working hypotheses, associated with each attribute, have been developed to guide the testing of remaining issues. The hypotheses provide a basis for organizing, managing, and explaining the rationale for testing and analyses related to total system performance. It should be recognized there are strong interdependencies among the attributes and the associated hypotheses. Because this strategy is one of defense-in-depth, lack of support for any single hypothesis will not necessarily indicate unacceptable performance. Each hypothesis and attribute must be evaluated in the context of its relative contribution to the performance of the total system.

The following discussion outlines the approach for evaluating each key performance attribute by summarizing the current evidence and identifying the remaining issues in the form of testable hypotheses. The approaches to testing and analyses that can be used to evaluate the hypotheses are reviewed at the end of this summary.

3.1 Seepage

Performance assessments have shown that seepage into the emplacement drifts is the most important determinant of the ability of the site to contain and isolate waste. This process ultimately affects all aspects of performance from waste package lifetime to radionuclide movement. The original conceptual model for the Yucca Mountain flow system was developed more than ten years ago -- a schematic representing this model is provided in Figure 3. Site

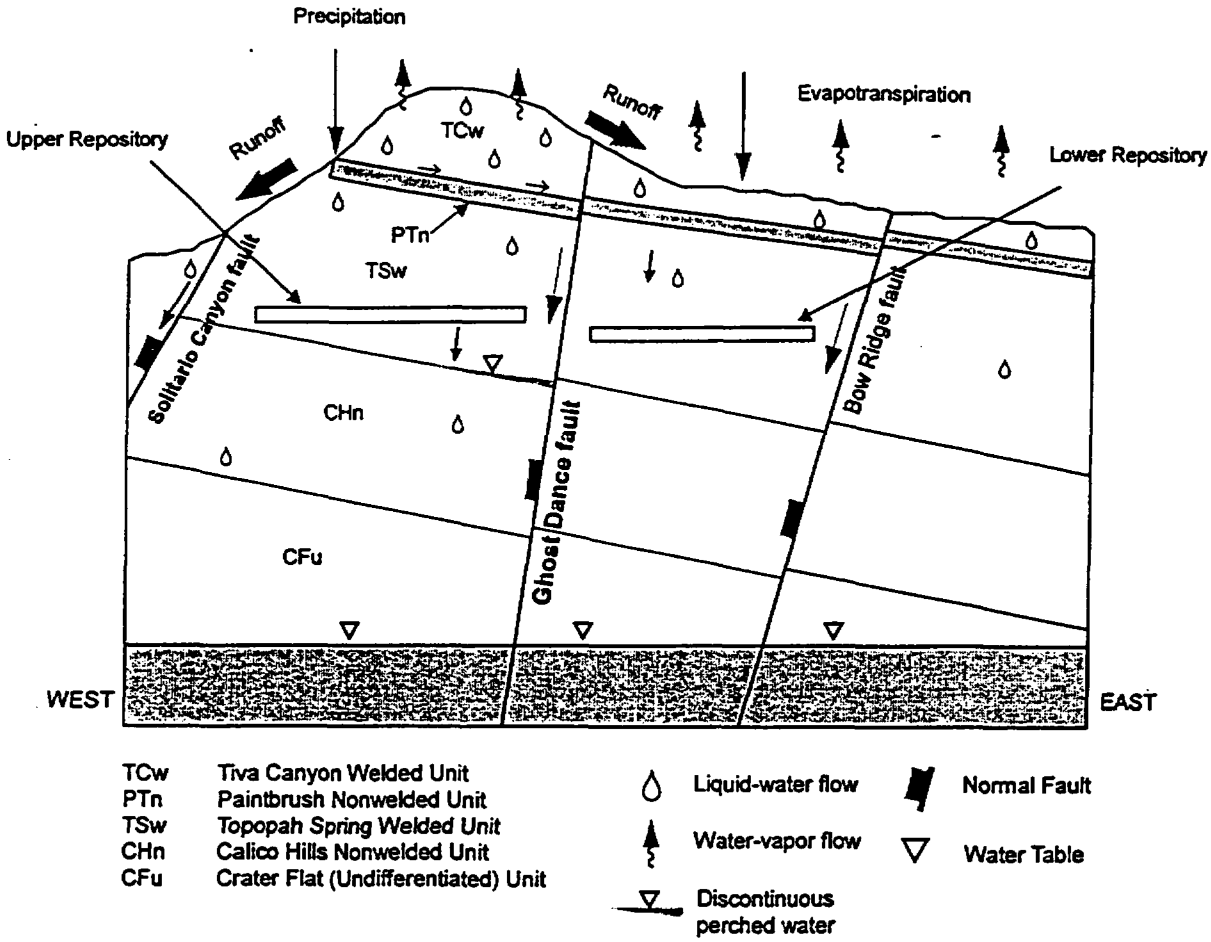

Figure 3. Conceptual model of flow at the Yucca Mountain site (modified from Montazer and Wilson, 1984.)

characterization information gained since the original model was developed provides additional support for this general view of Yucca Mountain.

Percolation flux -	volume of water moving downward and/or laterally through the unsaturated zone in a given time period
Seepage -	portion of percolation flux entering the emplacement drifts in a given time period

The amount of seepage into the repository depends, in part, on the amount of precipitation at the surface and the percentage of water that actually becomes net infiltration by avoiding runoff and evaporation. Climate change is assumed to cause temporal variations in the amount of net infiltration. Net infiltration may be reduced below the zone of evapotranspiration through barometrically driven gaseous exchange processes. The amount of percolation flux at repository depth also depends upon how water moves through the subsurface at Yucca Mountain. The competition between gravitational and capillary forces determines whether water moving downward travels primarily in fractures or in the matrix. Downward percolation flux may also be diverted laterally by units with contrasting hydrologic properties. If laterally diverted water is captured in steeply dipping fracture zones, downward flow will concentrate in these zones, but the limited amount of water available places bounds on the number of such zones and the flux they collectively transmit. New information from isotope ratios in samples from fracture coatings and pore-water ages in the Exploratory Studies Facility will be useful in determining the spatial and temporal frequency of fracture flow at repository depths. The amount of seepage into drift openings may be further limited by the tendency for the water, due to capillary forces, to remain in the small pores of the rock and thus flow around the drift openings, rather than into them. Performance assessment results show this diversion effect to be important, particularly for low flux conditions.

It is important to recognize that heat from the radioactive waste is expected to mobilize water in the host rock and drive this water away from the repository. Water mobilized while the temperatures are high may return after the temperatures decrease. If the water does not return, or if the return flow is through the matrix and therefore very slow, seepage could be less than under ambient conditions. If the water returns quickly, within a time comparable to the initial mobilization period, percolation fluxes higher than ambient could occur.

The specific hypotheses to be addressed regarding seepage are as follows:

1. Percolation flux at repository depth is significantly less than net infiltration.

2. Fracture flow occurs within a limited volume of the repository host rock at any given time.

3. Seepage into the emplacement drifts will be limited to a small fraction of the incident percolation flux due to capillary forces.

4. Bounds can be placed on thermally-induced changes in seepage rates.

5. Impacts of climate change on seepage rates can be bounded.

3.2 Containment

As long as waste packages remain intact, the waste will be completely contained and prevented from any contact with the host rock or the ground water. Test and modeling information that is already available suggests that containment times exceeding 1,000 years are feasible. The current waste package design is double-walled with a thick corrosion-allowance outer barrier surrounding a corrosion-resistant inner barrier. This design approach provides redundancy because the outer barrier protects the inner barrier from environments that can cause increased corrosion rates. A double-walled waste package may also offer galvanic protection of the inner barrier by the outer barrier if the design and materials are suitably chosen. These effects can extend the lifetime of the inner barrier for a period estimated to be several thousand years, according to recent performance assessment results (Andrews et al., 1995).

> Double-walled waste package designs may extend the lifetime of the inner barrier for thousands of years.

In the first few thousand years, heat is expected to mobilize water in the host rock and drive this water away from the repository. Humid air corrosion rates are known to be lower than aqueous rates, particularly at low relative humidity, and current analyses predict relative humidities below 60 percent for hundreds to thousands of years (Andrews et al., 1995; Buscheck et al., 1995). As noted in Section 3.1, after temperatures decrease, water mobilized while the temperatures are high may return to the waste package environment at rates that are less than, equal to, or more than the current seepage rates. Engineered system enhancements that would prolong the period of low humidity or delay liquid water contact could provide increased confidence in long-lived waste packages. Introduced or naturally occurring microorganisms that were dormant during the thermal period may colonize under warm and humid conditions and enhance waste package corrosion.

The following hypotheses are posed to address the containment-related issues that need further resolution:

6. Heat produced by emplaced waste will reduce relative humidity in the vicinity of waste packages.

7. Corrosion rates are very low at low relative humidity, and corrosion of the inner barrier is slow.

8. Double-walled waste packages will significantly increase containment times due to protection of the inner barrier by the outer barrier.

3.3 Radionuclide Mobilization

Performance assessments show that the rate of mobilization of radionuclides from the waste form is one of the key factors determining the annual peak dose. The strategy therefore focuses on mobilization of those radionuclides that potentially make a significant contribution to the peak dose. Of much less concern is mobilization of radionuclides that are short-lived or that are not effectively transported after initial mobilization, as well as those that are mobilized in the gas phase and that travel as gases. The one exception may be iodine, which in recent performance assessments has been identified as possibly contributing significantly to annual peak dose because it may move rapidly away from waste packages as a gas and then dissolve into the ground water in the surrounding rock.

Solubilities of radionuclides most important to performance have been measured or bounded. The approach in this strategy is to focus on verifying the dissolution rate of spent fuel, which is expected to control the dissolution rates of most of the more soluble radionuclides. Dissolution of vitrified high-level waste is not a significant issue because current evidence shows that the radionuclide content of this waste is much less than that of spent fuel for the critical radionuclides that contribute to peak doses.

Using available data, dissolution rates of irradiated uranium oxide were developed for a range of temperatures and water chemistries in the repository. Preliminary measurements of the dissolution rates of soluble species from spent fuel under unsaturated conditions suggest that the mobilization rates can be satisfactorily bounded for the purpose of performing total system analyses. Certain radionuclides could be mobilized more rapidly than the spent fuel dissolution rate. This is true for soluble species that reside in the grain boundaries of the fuel pellets or that are subject to surface effects that lead to preferential leaching. However, the most important of these is cesium, and measurements show a leach rate that is no more than about twice the estimated spent fuel dissolution rate.

There are a number of issues associated with the estimation of the radionuclide mobilization rates. Dissolution of the radionuclides is a direct function of the surface area exposed and the amount of water that contacts the waste. The presence of cladding will significantly reduce the surface area of spent fuel available for release of radionuclides. An important issue regarding the dissolution rate of spent fuel is the potential for alteration to forms that dissolve more rapidly. Measurements show that the dissolution rate of unclad spent fuel that has been altered to U_3O_8 is significantly greater than that of uranium dioxide, although the net increase in the dissolution rate in a repository setting is not known at this time. If the waste is fully contained during the early period of high temperatures, this will limit the availability of oxygen and inhibit alteration of the spent fuel. Using this logic, the length of containment relative to the temperature in the waste package becomes a key issue for mobilization rates. One source of uncertainty that must be evaluated is the potential for microbial activity or introduction of man-made materials into the repository to affect water chemistry in a way that increases mobilization rates.

Evidence suggests that colloid formation could result in initial mobilization rates of some radionuclides, particularly the actinides, that are higher than those defined by their solubility. However, the stability of true radiocolloids under repository conditions has not yet been determined. Some information suggests that under repository conditions, these colloids would either not be stable, or would occur in low enough concentrations so as not to provide a means to effectively mobilize radionuclides (Triay et al., 1995).

Tests of hypotheses related to seepage and containment will provide part of the basis for evaluating this attribute. Additional issues described above require that the following hypothesis be addressed:

9. Radionuclide release from waste forms due to surface area exposed, dissolution, colloid formation, and microbial activity will be low.

3.4 Radionuclide Transport

The potential dose depends directly on the concentration of radionuclides in the water. These concentrations change as the radionuclides migrate from the repository to the point of potential uptake by individuals using the water. In general, heterogeneities in the flow and transport properties cause dispersion and spread the radionuclides out in space and time, reducing the concentrations. Dispersive mixing due to interactions between fracture and matrix flow and spatial heterogeneity may reduce radionuclide concentrations by as much as two orders of magnitude below those produced by limited dissolution rates and solubilities of the radionuclides (Andrews et al., 1995; Robinson et al., 1995).

Concentrations will also be reduced by depletion of radionuclides during transport, either due to radioactive decay and/or by matrix diffusion and sorption. Sorption is a chemical bonding of the radionuclide to the minerals present in the rock mass, whereas matrix diffusion involves movement of radionuclides from flow in the fractures into the pores of the rock matrix. Both of these processes reduce radionuclide concentrations and thus contribute to dilution in the unsaturated and saturated zones. Because sorption is probably reversible for most of the poorly sorbing radionuclides, the net effect on transport is to delay the arrival of the radionuclides at the accessible environment. Under favorable circumstances in which the percolation flux is low, this delay can result in a reduction in the peak dose. Combining this with the effects of diffusion, dispersion, and radioactive decay, the concentrations of poorly sorbed radionuclides are expected to be reduced by several orders of magnitude after traveling through the natural barriers (Robinson et al., 1995). For highly sorbing radionuclides, the concentrations are reduced by many more orders of magnitude. For many of the radionuclides, removal can be considered permanent. In the case where the sorption reaction is found to be reversible, rates of desorption must be considered. It should be noted that when desorption occurs, the radionuclide then travels with the water and can be sorbed again. Generally, the rate of sorption is larger than the rate of desorption, resulting in a net mass removal of radionuclides from the downward moving water.

- Dispersive processes reduce concentrations of radionuclides during transport.
- Depletion refers to processes that lead to the effective removal of radionuclides as potential contributors to dose.

For those radionuclides with limited potential for sorption (iodine, technetium, neptunium), the potential for use of enhanced engineered barriers could be considered. Measurements have shown that diffusion occurs in transport through engineered materials such as backfill. Measurements of tuff gravels show that in cases where there is no advection, diffusion across the surface of partially saturated gravel fragments is very slow, with diffusion coefficients that are many orders of magnitude below those for saturated liquid diffusion. Experimental evidence shows that diffusion is a strong function of water content at low saturations (Conca, 1990). At low water contents, transport occurs in thin films of water on the surface of the fragments, and mass transport, which depends on the film thickness, is much slower than in fully saturated media.

There are issues that must be resolved before diffusion or depletion can be demonstrated to be effective. The first and most important issue is the moisture conditions (flow rates and saturations) in the engineered barriers. The seepage rate into the emplacement drifts must be bounded and the associated saturations must be determined. Second, the flow and transport characteristics of the engineered barriers need to be determined for these conditions. While considerable data exist for transport under saturated conditions, these observations need to be extended to repository conditions. Third, although there is some information regarding the depletion potential of the engineered barriers, the tests have been for short periods and may not reflect equilibrium conditions. Additional information is needed to verify that laboratory-determined sorption and desorption effects result in depletion under repository conditions.

These questions must be addressed in an integrated evaluation. This evaluation requires that the following hypothesis regarding radionuclide transport characteristics be addressed:

10. Transport properties of both engineered and natural barriers will significantly reduce radionuclide concentrations due to depletion, diffusion and dispersion.

3.5 Dilution

If the amount of water seeping into the emplacement drifts and contacting the waste is small, the radionuclide concentration will be reduced when this small flow is added to the larger flow below the water table. This dilution depends upon the degree of mixing of the flow containing the radionuclides with the flow below the water table, and also upon the dispersion of the radionuclides during transport in the receiving flow. The strategy focuses on determining the ratio of the flow that may contact the waste to that in the receiving aquifer and the potential for advective mixing and dispersion of radionuclides in the aquifer.

> Dilution is an important factor that can reduce radionuclide concentrations and limit annual dose.

It will be important to demonstrate that significant flow is occurring in the saturated zone in order to dilute the radionuclide-bearing flux that percolates to the water table. Flow velocities have been estimated to be on the order of several meters per year on the basis of regional modeling (Czarnecki and Waddell, 1984; Barr, 1994). The magnitude of mixing and dispersion must also be established because certain conditions have been noted to lead to persistence of contaminant plumes (Maqarin Study Group, 1992). However, persistent contaminant plumes may themselves be subject to significant dilution when mixed with other water in a producing well.

These questions can be addressed by testing the following hypotheses:

11. Flow in the saturated zone is much greater than the flow contacting the waste.

12. Water percolating down through the repository horizon to the water table mixes with the flow in the aquifer.

4. EVALUATING DISRUPTIVE PROCESSES AND EVENTS

The strategy must also address potential disruptions to the system that could release radionuclides directly to the accessible environment or otherwise adversely affect the characteristics of the system. Because the climate at Yucca Mountain is expected to change with time, climate change is not treated as a disruptive process in this strategy. The potential impact of future climate changes on percolation flux at repository depths was included as an hypothesis in Section 3. Data already acquired for the site are sufficient to provide probabilities of tectonic activity and volcanic eruptions. Analyses are needed, however, to support assessments of the potential effects of such disruptions on the predicted doses to the public. Because Yucca Mountain is not regarded to be a future target for resource exploration, no hypotheses related to human interference are identified in this strategy.

4.1 Tectonics and Seismicity

The strategy to address tectonic processes is based upon their likelihood and potential effects. Waste containment and isolation could be directly affected by movement on faults or ground motion related to earthquakes. The likelihood and magnitude of such fault movement or ground motion can be inferred from the geologic record of Quaternary movement on known faults at or near the site. The approach is to determine if potential movement on faults that extend through the repository horizon would have sufficient magnitude and frequency to adversely impact waste packages during the period they are relied upon to fully contain the waste.

Quaternary Period - the last two million years	
Pliocene Epoch -	the period between about five million years ago and two million years ago

Estimated average Quaternary displacement rates on faults near the site, such as the Bow Ridge and the Solitario Canyon faults, range from .001 to .02 mm/yr. Displacements per event range from a few centimeters to about a meter, with recurrence intervals of tens of thousands of years (Pezzopane, 1995). Slip rates of this magnitude on a fault that might intersect the repository would be insufficient to transport waste to the surface, even over a period of hundreds of thousands of years. While fault displacements of this magnitude could possibly affect waste package containment, the long earthquake recurrence intervals indicate that adverse impacts on containment during the first several thousand years are highly unlikely. Fault displacements of lesser magnitudes may contribute to increased rockfalls or localized drift collapses, but these events are not expected to compromise containment or waste isolation performance.

Significant seismic effects on the flow system are not expected. The hydrologic flow system has been subjected to seismic activity throughout the Quaternary Period, and it is considered unlikely that future seismic activity will result in large changes to the regional ground-water flow system or the local unsaturated zone flow system at Yucca Mountain. Water table response to the 1992 Little Skull Mountain earthquake was small, and the water table returned to its ambient state within hours. The National Academy of Sciences (1992) examined available evidence for water table rise and concluded that seismic events could produce transient effects on the water table, but that the maximum transient rise in the past was probably less than 20 meters. The proposed repository horizon is planned to be more than 200 meters above the water table. Effects on the large hydraulic gradient north and northwest of the site have also been examined. Modeling the effects of a "release" of the water associated with the steep gradient produces an increase in water table elevation of less than 30 meters in the vicinity of the repository, which would not significantly affect waste isolation. The large hydraulic gradient is thought to have persisted through numerous earthquakes in recent geologic history. Similarly, hydrologic characteristics of faults and fractures at Yucca Mountain represent the cumulative effect of numerous tectonic events. Future events are unlikely to significantly change those characteristics.

> Increases in water table elevation due to seismic effects can be bounded at 20-30 meters, which would have no adverse impact on performance.

The hypotheses to be evaluated for tectonics and seismicity are:

13. The amount of movement on faults through the repository horizon will be too small to bring waste to the surface, and too small and infrequent to significantly impact containment during the next few thousand years.

14. The severity of ground motion expected in the repository horizon for tens of thousands of years will only slightly increase the amount of rockfall and drift collapse.

4.2 Volcanism

Volcanism at the site could result in direct releases of radionuclides from the repository system as well as indirect effects due to fluids that might accompany the volcanic activity. The strategy is to infer the probability of volcanic events within the repository boundaries from the geologic record and to estimate the consequences of such an event, were it to occur.

Crowe et al. (1995) summarized the work to date on past volcanic activity in the Yucca Mountain region. They estimated that the probability of a basaltic volcanic eruption within the immediate vicinity of the repository has a mean value of about 10^{-8} events/yr. In addition, they concluded that the volumes of erupted magma within the Yucca Mountain region have decreased exponentially since the Pliocene Epoch, although there may be a slight increase in frequency of eruptive events during the Quaternary Period. Available information suggests that volcanism has been drifting to the west for the last 3 to 4 million years. If this trend continues into the far future, the probability of a volcanic event disrupting Yucca Mountain will be even less than currently estimated.

Volumes of erupted magma have decreased significantly over the last five million years.

Because the possible entrainment of waste during an eruption is of most concern, the volume of magma and the change in eruptive volume through time is considered to be a useful indicator of potential effects. The existing data are sparse because of the low frequency of volcanic events. Crowe et al. (1995) concluded that additional field evidence in the area is unlikely to change the probability values they have estimated because of the large uncertainties associated with a result based on a limited data set.

Barnard et al. (1992) evaluated the consequences of direct effects of a basaltic magmatic intrusion into the repository. They evaluated releases from an event in which waste is entrained and subsequently exposed at the surface. In this evaluation, the calculated releases were small, on the order of the release limits specified in the remanded standard that formerly applied to the Yucca Mountain site (40 CFR Part 191). Wilson et al. (1994) evaluated releases resulting from magmatic off-gassing and heat flow impacts and concluded that indirect effects due to volcanism are of little consequence to system performance.

The evaluations of consequences have so far considered only radionuclide releases, not radiation doses. These assessments also considered that any waste on the surface was a release. No calculations of the consequences of volcanism on repository performance have been done that would be useful for comparison to a dose or risk standard. To evaluate the consequences of volcanism relative to a dose standard, a model is required for how humans might be exposed, for example by breathing air-borne dust, or drinking contaminated runoff water. To adequately evaluate the risk of volcanism, a dose model must be applied to Yucca Mountain to evaluate consequences, and consequences must then be normalized to the probability of a volcanic event at or near Yucca Mountain.

The hypothesis to be evaluated in this case is:

15. Volcanic events within the controlled area will be rare and the consequences of volcanism will be acceptable.

4.3 Human Interference

The National Academy of Sciences (1995) considered human interference issues and concluded there is no scientific basis for projecting human activity thousands of years into the future. They turned their attention to whether analysis of the consequences of human interference could provide a useful basis for evaluating a proposed repository site and design. They concluded that the calculations of consequences would provide useful information about how well a repository might perform after an intrusion occurs.

While it is true that there is no scientific basis for projecting human activity thousands of years into the future, the continued existence and profitability of resource exploration companies depends upon the ability to assess whether sites are likely candidates for future resource development. Therefore, it is assumed that the approaches used by such companies provide a useful indicator of how explorations and assessments would be conducted, at least in the near future. While no data or analyses can guarantee that human intrusion will not occur in the future, or even predict its probability, the approach in this case is to determine if Yucca Mountain is likely to be of interest for future resource exploration or development in the foreseeable future.

The Yucca Mountain site and region have been assessed with regard to resource potential (DOE, 1986; Castor et al., 1989; Younker et al., 1992). None of these evaluations have suggested that the site is a likely target for future exploration. Given these resource assessments, no hypotheses regarding human interference are proposed.

4.4 Nuclear Criticality

The presence of fissile radionuclides such as uranium-235 and plutonium-239 in the radioactive waste means that an evaluation must be made regarding whether a sustained neutron chain reaction (a criticality event) could occur. The results of a criticality event involves the local generation of heat and an increase in the fission product inventory. No realistic scenario has been developed through which such an event could significantly affect waste isolation. The strategy to address such criticality focuses on the conditions needed to support the criticality reaction.

Analyses to date indicate that the probability of criticality under dry conditions is very low for commercial spent nuclear fuel disposal. If water is not available to transport radionuclides, the fissile radionuclides would remain in the waste packages, and there is an insufficient quantity of plutonium-239 or uranium-235 in the commercial spent fuel waste packages to support a sustained reaction without water moderation (Sanchez, 1995). Even if some water is available, the amount of water would need to be sufficient to remove the neutron absorbing materials in the waste package.

Likewise, the probability of criticality if fissile radionuclides are transported outside of the waste package is expected to be low. A criticality event is considered unlikely in the near-field, especially if a backfill is included in the engineered barrier design. The potential far-field criticality case depends upon the deposition of fissile material from multiple waste packages along transport pathways in the host rock. The probability of a criticality event occurring under this condition should remain low. The formation of a critical configuration of fissile material in the far-field requires adequate moderation and mechanisms for removing the neutron absorbing isotopes intrinsic to the spent fuel.

The evaluation of the potential for a criticality reaction requires information about the characteristics of the waste form, the corrosion of waste packages, and the dissolution and transport of fissile radionuclides and neutron absorbers. Information needed to evaluate transport of radionuclides through the rock units underlying the repository will be obtained to evaluate the hypotheses related to seepage, containment, mobilization, and transport. This information can be used to determine the likely environments and geometric configurations of the mobilized radionuclides to establish the probability of criticality, and if necessary, the consequences within the context of total system performance.

5. IMPLICATIONS OF THE UPDATED STRATEGY

Improved site understanding and maturation of design concepts for the engineered system provide the basis for more realistic performance predictions. Using recent performance assessment predictions, the key attributes of the natural and engineered system have been identified. For each attribute, the major questions that remain to be answered have been captured as testable hypotheses. Percolation flux at repository depth, and how this is reflected as seepage into the emplacement drifts, continues to be the key system attribute impacting performance. If the seepage is as small as current interpretations suggest, and remains small through future climate and thermally-induced changes, waste packages will corrode very slowly and waste will be contained in them for thousands of years. Even when waste packages eventually fail, multiple lines of defense provided by solubility limits of the radionuclides, dispersion and depletion during transport, and dilution are expected to result in acceptably low annual doses.

Understanding the key attributes affecting waste containment and isolation will also allow us to evaluate improvements that could enhance total system performance. In particular, evaluations of the hypotheses may have implications for the design of the waste packages, the need for backfill or other engineered barriers, or the density of heat-generating waste in the repository or in individual waste packages.

Definition of the hypotheses in this strategy enables us to focus a testing and analysis program on the key remaining questions related to repository performance. The information sources most useful for testing the hypotheses are summarized in Table 1. The tests and analyses include numerical modeling of processes at detailed levels and as a total system, laboratory testing to constrain key parameters, observations and *in situ* tests in the Exploratory Studies Facility and other underground locations, and other field tests. Boxes in Table 1 containing a single check mark represent sources where only limited information is currently available and substantial additional information will be needed to evaluate the hypothesis. Two check marks identify areas where substantial information exists and additional testing or analyses are expected to improve and confirm current understanding. Three check marks indicate areas where testing or analyses to support the current phase of the program are essentially complete, although future performance confirmation requirements could lead to reopening of some areas. Ongoing planning of the scientific program will lead to a more detailed delineation of the remaining testing and analysis programs needed to evaluate the hypotheses. Existing data, combined with the results of additional tests and analyses, will be compiled, interpreted and synthesized to provide the parameters and models for an evaluation of waste containment and isolation that becomes more comprehensive with time.

Attribute	Hypotheses to be Evaluated	Type of Testing or Analysis			
		Numerical Modeling	Laboratory Testing	ESF/In situ Observations & Testing	Surface-based Field Testing
Seepage	1. Low percolation flux at repository depth	✓✓	N/A	✓	✓✓✓
	2. Limited fracture flow at repository depth	✓✓	N/A	✓✓	✓✓✓
	3. Capillary retention reduces seepage into drifts	✓	✓✓	✓	N/A
	4. Thermally induced flux can be bounded	✓✓	✓	✓	N/A
	5. Effects of climate change can be bounded	✓✓	N/A	✓	✓✓
Containment	6. Low humidity at waste package surface	✓✓	✓	✓	N/A
	7. Slow corrosion at low humidity	✓	✓	N/A	N/A
	8. Galvanic protection of inner barrier	✓	✓	N/A	N/A
Radionuclide Mobilization	9. Low mobilization rates from waste forms	✓✓	✓✓	N/A	N/A
Radionuclide Transport	10. Radionuclide concentrations reduced by depletion and dispersion	✓✓	✓✓	✓	N/A
Dilution	11. Flux in saturated zone >flow contacting waste	✓	N/A	N/A	✓
	12. Strong mixing occurs in saturated zone	✓	N/A	N/A	✓
Disruptive Processes & Events					
Tectonics & Seismicity	13. Fault displacement impacts not significant	✓✓	N/A	✓	✓✓✓
	14. Minimal ground motion impacts	✓✓	N/A	N/A	✓✓✓
Volcanism	15. Consequences of volcanism limited	✓✓✓	N/A	N/A	✓✓✓

Table 1. Information sources for testing hypotheses: ✓ = limited information exists; ✓✓ = substantial information already available; ✓✓✓ = work essentially complete for current phase of program; N/A = not a significant information source.

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