Yucca Mountain Licensing Standard Options for Very Long Time Frames

Technical Bases for the Standard and Compliance Assessments

Technical Report

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1011754

Interim Report, April 2005

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This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Yucca Mountain Licensing Standard Options for Very Long Time Frames: Technical Bases for the Standard and Compliance Assessments, EPRI, Palo Alto, CA: 2005. 1011754.

REPORT SUMMARY

In the existing U.S. Environmental Protection Agency (EPA) and Nuclear Regulatory Commission (NRC) regulations governing the spent nuclear fuel and high level radioactive waste site at Yucca Mountain, Nevada, the time period of compliance was set at 10,000 years. On July 9, 2004, the DC Circuit of the U.S. Court of Appeals ordered that the EPA and NRC either revise the regulation on this topic to be "based upon and consistent with" recommendations made by a panel of the National Academy of Sciences (NAS)—which recommended a time period of compliance out to as long as one million years—or seek congressional relief. This report summarizes the technical issues and makes recommendations related to establishing a meaningful, reasonable, and implementable standard for such a long time period of compliance, assuming no congressional action is taken.

Background

Congress directed the EPA to contract with the NAS to provide recommendations on the technical bases for the Yucca Mountain standards. In its 1995 recommendations report, the NAS discussed many technical issues related to the time period of compliance. The NAS noted that most "physical" and geologic processes were "stable" and "predictable" at Yucca Mountain for times up to one million years. The NAS suggested two approaches for dealing with processes that were less predictable over these time periods: specify them via EPA rulemaking (such as future human actions), or use "bounding" approaches (such as for climate-related issues).

Objectives

- To evaluate the technical issues related to establishing a meaningful, reasonable, and implementable standard for Yucca Mountain for a time period of compliance up to one million years in the future.
- To recommend specific regulatory approaches that the EPA and NRC could take along with feasible compliance assessment approaches for the U.S. Department of Energy (DOE).

Approach

EPRI reviewed the recommendations made by the NAS panel in an effort to understand the panel's approach to long-term uncertainties at Yucca Mountain. The NAS recommended three basic approaches to dealing with those uncertainties. First, they suggested the use of probabilistic methods to quantify the range of uncertainty and variability for those processes that are "predictable" over one million years. For processes that are less predictable over such a long time period, they recommended application of either bounding approaches or regulatory rulemaking to essentially fix the scenario or assumptions made in a compliance assessment. While NAS guidance on probabilistic and rulemaking approaches was reasonably clear, its guidance on the use of bounding approaches was less so. EPRI supplemented the NAS guidance on the use of bounding approaches with guidance by other organizations to develop a more direct way of dealing with less predictable processes. The primary example EPRI considered was long-term climate change. EPRI also considered alternative approaches to establishing which features, events, and processes (FEPs) need to be considered in a compliance assessment model as well as alternative dose limits for the very far future.

Results

Some components of the Yucca Mountain system, particularly future climate at the site, will need to be treated in a fundamentally different manner if the time period of compliance is extended beyond 10,000 years. This is because uncertainties related to the estimate of peak health (or dose) risk grow with time out to roughly the time of peak risk. For example, uncertainties in future climate states (magnitude and rate of change) increase in the future, but especially so for time periods beyond the order of 10^4 years. There is almost universal agreement that a more “stylized” approach to developing methods for assessing very long-term repository performance needs to be adopted, due to increased uncertainty in the far future.

In light of this, EPRI recommends that future climate state(s) be established by rulemaking in a manner similar to that used to establish bounds on future human behavior. Specifically, EPRI recommends that future climate be fixed to the present interglacial classification, since such an action avoids a large amount of speculation about future climate details and the associated human behavior. Furthermore, the present climate state is likely to reasonably bound future dose risks. EPRI also recommends a different approach to establishing which FEPs will be included in a compliance assessment – one that is based on the concept of Negligible Incremental Dose recommended by the NAS panel. Finally, EPRI notes that arguments can be made for a different, higher dose limit to future generations that is still protective of human health.

EPRI Perspective

EPRI believes that the partially remanded EPA and NRC regulations for Yucca Mountain already provide a high degree of protection for future human populations, as evidenced by the DOE’s move to a robust engineered design to achieve compliance with the remanded regulations. The very nature of this design causes peak dose risks to members of the public to be shifted out to very long time periods – time periods where uncertainties in being able to “predict” future system behavior increase. It is necessary, therefore, for a meaningful, reasonable regulation to maintain a high degree of protection while not penalizing a design that provides a large amount of radionuclide retention and/or delay time prior to entry into the biosphere. This requires a different approach to regulation and compliance assessment, rather than simply extending the time period of compliance to the time of peak dose. A revised approach can be taken that is “based upon and consistent with” the NAS recommendations.

Keywords

Yucca Mountain
High Level Radioactive Waste
Spent Fuel Disposal
Total System Performance Assessment

EXECUTIVE SUMMARY

This report has been developed to address the ramifications of the July 9, 2004 decision by the US Court of Appeals, District of Columbia Circuit, vacating the provision in regulations 40 CFR 197 and 10 CFR 63 that established a regulatory compliance period of 10,000 years for the proposed spent nuclear fuel (SNF) and high-level radioactive waste (HLW) repository at Yucca Mountain, Nevada (US Court of Appeals, 2004).

The purpose of this report is to consider technical implications and options associated with regulatory compliance periods in excess of 10,000 years that:

- Are consistent with the Court of Appeals ruling;
- Result in a "meaningful" standard that protects public health and safety in a constructive and equitable manner; and
- Would be "reasonable" and implementable in a regulatory environment.

This report does not revisit issues settled in the Court of Appeals ruling. Rather, the report addresses potential regulatory approaches for implementing the ruling that are based upon and consistent with the recommendations made by the National Academy of Sciences (NAS) panel on the Technical Bases for Yucca Mountain Standards (TYMS) in its 1995 report (TYMS, 1995).

This report provides arguments that some components of the Yucca Mountain system, particularly future climate at the site, will need to be treated fundamentally differently if the time period of compliance is extended beyond 10,000 years. This is because uncertainties *related to the estimate of peak health risk (dose risk)* grow with time out to roughly the time of peak risk. For example, uncertainties in future climate states (magnitude and rate of change) increase in the future, but especially so for time periods beyond the order of 10^4 years.

While the TYMS panel makes a large number of recommendations related to the technical bases for the standard, there are a few recommendations that are especially relevant to the Court's decision. This report will focus on these recommendations as follows:

- The time period of compliance should extend to the time of peak individual health risk, or one million years, whichever comes first. The selection of this time period is related to the stability of the physical and geologic systems;
- The standard should be "meaningful." Meaning is provided by the form of the standard (individual health risk), and a compliance assessment based on conceptual and numerical models that reasonably reflect present-day understanding of the features, events, and processes (FEPs) that occur, or are reasonably likely to occur during the time period of

compliance. EPA elected to use a limit on annual individual radiological dose rather than individual health risk.

- The concept of Negligible Incremental Risk (NIR) was recommended by TYMS to screen FEPs to be considered in performing the compliance assessment. If the risk (consequence weighted by its probability) was less than some value to be established by EPA, then that particular FEP need not be considered in the compliance assessment. Instead, EPA specified that a FEPs screening cutoff based entirely on probability of approximately 10^{-8} per year be used;
- Some FEPs of the Yucca Mountain system necessary to perform an individual health risk assessment over very long time frames are less well understood than the geologic and some of the engineered FEPs. Examples of less understood FEPs mentioned by the TYMS panel are: future human behavior, seismicity, igneous processes, and climate. The TYMS panel recommends that these FEPs be either fixed in rulemaking, as specifically recommended for human behavior, or somehow “bounded,” as TYMS implied should be done for seismicity, igneous processes, and climate.

The core of this report focuses on the TYMS panel recommendations on how to address, via regulation and/or compliance assessment, these less well understood FEPs while still conducting a “meaningful” compliance assessment for a time period as long as one million years.

The recommendations made by the TYMS panel related to the use of rulemaking to settle the issue of what future human behavior to assume are quite clear. Since it is necessary to calculate dose risks, it is necessary to convert radionuclide concentrations in groundwater or the atmosphere into an individual health risk. This requires estimates of how the radionuclides enter the human body via, for example, drinking water, food, or inhalation. It also requires estimates of the health risk (dose) imparted by those radionuclides once they have entered the body. Thus, one needs to postulate what humans will be doing (“human behavior”) in the far future that will cause human exposure to the radionuclides, along with the “health risk (or dose) consequences” once those radionuclides have entered the body. There are significant uncertainties in determining both sets of parameters. For both major components of estimating health risk (or dose), the TYMS panel recommended the use of fixed assumptions to be established by rulemaking. The TYMS panel recommended that a “critical group” concept be used in which EPA was to specify the behavior of that group (activities that would expose the group to contaminated groundwater, soil, or air). Furthermore, the TYMS panel recommended that some standard conversion between ingested or inhaled radionuclide concentration and health risk (dose) be used. EPA adopted these recommendations and specified the human behavior to be assumed in the compliance calculations, along with the use of standard dosimetric conversions.

The TYMS panel went to great lengths to explain their reasoning behind recommending the use of rulemaking to essentially “fix” the relevant aspects of future human behavior. They noted, “…it is not possible to predict on the basis of scientific analyses the societal factors required for an exposure scenario.”

In the versions of 40 CFR Part 197 and 10 CFR Part 63 using the 10,000 year standard that the Court has addressed, rulemaking has been used to establish fixed future human behavior characteristics and future human health risk (dosimetric) responses to individual radionuclides. Yet while the TYMS panel also recommended that “bounding” analyses could be used in considering seismic, igneous, and climatic processes, neither EPA nor NRC provided any guidance to DOE on how to "bound" these processes. In the absence of any guidance from EPA or NRC, DOE developed rather elaborate seismic, igneous, and climate models that were focused on the first 10,000 years after repository closure. While DOE used these models to develop dose estimates out to one million years in the Yucca Mountain Final Environmental Impact Statement (FEIS), the use of these models resulted in a gross overestimation of doses in these time frames. Given that the purpose of the FEIS was not to determine regulatory compliance there was no need to develop a better approach to these particular models.

There would be such a need if the time period of regulatory compliance is extended beyond 10,000 years without further guidance.

Future climate evolution beyond 10,000 years is among the key issues that need to be addressed. The peak environmental impacts DOE shows in the FEIS are dominated by the assumptions DOE made with respect to the timing and rate of change from one climate state to the next. This is contrary to the expectation of the TYMS panel, which, based on the information that was available in 1995, opined that only minor impacts on the mean health risk (dose risk) estimates would occur due to changes in climate states. EPRI's independent analyses suggest that the large, multiple peaks shown in DOE's FEIS analyses are modeling artifacts. An approach that results in such artifacts is unacceptable if a "meaningful" approach to demonstrating safety through a regulatory compliance assessment beyond 10,000 years is to be achieved. This report suggests that uncertainties in the characteristics of future climate states (timing and rate of change from one state to the next) increase significantly beyond the order of 10^4 years in the future. This is roughly at the time when it becomes more likely that there will be a major climate shift. However, the magnitude of that shift and the rate of change from the current climate state to the new climate state – both important properties in at least the DOE dose risk estimate model – are not well known, although they may be somewhat "boundable." However, the details of human behavior are expected to change as a result of climate change; to a lesser extent, climate change may be linked to future human behavior. It is therefore seen that the details of climate change and the details of human behavior are closely linked. Therefore, in this report, it is proposed that future climate characteristics be established using rulemaking in a manner similar to that already done for human behavior and dosimetry.

Adding to the difficulty of combining probabilistic and "bounding" approaches in a reasonable and implementable manner, the TYMS recommendations provide very little in the way of explanation regarding how to use "bounding" approaches for those FEPs less well known than the geologic ones. While the TYMS panel recommends a risk-based approach, the absence of more specific recommendations regarding the use of "bounding" approaches presents a significant challenge for EPA and NRC in the development and implementation of a regulatory approach to accomplish this. To supplement the TYMS recommendations, this report explores approaches used in other countries or by international organizations for dose estimates from repositories over very long time periods. In general, these other organizations refer to the need to use a "stylized" approach to dose estimates. Many of these organizations specifically mention either 1000 or 10,000 years as a time at which a stylized approach should be adopted. Fundamentally, the approach is based on the recognition that it becomes impossible to provide accurate estimates of the details of the evolution of natural and human systems over very long time frames. A "stylized" approach involves the use of a limited set of scenarios and allows for a more straightforward evaluation of the details of the models. The use of a limited set of scenarios is consistent with the TYMS panel general comments about the use of “bounding” approaches for those FEPs less certain than the geologic and some engineered FEPs. The recognition that a more simplified examination of the details of the models is appropriate at very long time periods is already implicitly recognized in both 40 CFR 197 and 10 CFR 63.

Thus, this report recommends that a more stylized approach to compliance model development be taken for time periods beyond 10,000 years. In particular, a fixed set of climate scenarios should be adopted. At most, only two scenarios are likely necessary to reasonably “bound” the effects of future climate: present-day “interglacial” and “glacial.” This is because the present-day climate results in the maximum human use of groundwater while the “glacial” climate would likely result in the maximum groundwater flow through the repository and to the compliance point. Given the surface water that would likely exist during a “glacial” climate in the Yucca Mountain vicinity, it is reasonable to assume that groundwater use would be dramatically lowered. Furthermore, given the large amount of dilution of any contaminants in the ground and surface water that would likely occur during the “glacial” climate, simply assuming the present-day “interglacial” climate exists for the entire duration of the compliance period would result in a reasonable upper bound on the effect of climate on peak dose risk.

The recommendation to fix the climate state in the compliance model to the present-day interglacial is based on the following considerations:

- Recent evidence suggests that net infiltration over time periods spanning multiple climate states has been more constant than previously understood;
- Biosphere dose conversion factors (converting, for example, groundwater concentrations into dose to the RMEI) for the present-day interglacial climate are reasonably bounding due to the relatively high use of groundwater and higher atmospheric dust loadings;
- The goal of maintaining an internally consistent compliance assessment requires that future human behavior be consistent with changes in the surface environment in different climate states. It would be impossible to avoid having to make largely arbitrary assumptions about such future human behavior as it doesn’t exist in the Yucca Mountain region today; and
- The *only* climate state for which more detailed information is available upon which to develop and defend net infiltration and biosphere models is the present-day climate.

The TYMS panel recommended adopting the concept of “Negligible Incremental Risk” (NIR) to screen FEPs and scenarios associated with the potential for widespread contamination. They based this recommendation on the existing concept of “Negligible Incremental Dose” (NID) that has been recommended by radiation protection organizations. The concept is that scenarios and FEPs that have a sufficiently low combination of probability and consequence need not be considered in the compliance analysis. Instead of directly adopting this recommendation, EPA adopted an alternative FEPs screening concept based purely on probability. That concept indicates that if the scenario or FEP has a probability of occurrence less than approximately 10^{-8} per year, then it can be eliminated from further consideration. This is a very low screening level compared to the NIR/NID level suggested by the TYMS panel as a reasonable starting point for discussion.

Thus, the current EPA screening limit is *very* conservative compared to the NID level suggested by the TYMS panel. It is likely that there are many FEPs that DOE has already “screened in” using the EPA approach that would not have been included if the TYMS-recommended approach were used. Given the overly inclusive approach to identifying FEPs that is already being used, it is unnecessary to further include any additional FEPs for time periods beyond 10,000 years. Given the increased uncertainties in the long time periods, even identifying FEPs with probabilities of occurrence as low as 10^{-8} per year will be difficult. In any case, if EPA requires additional FEPs screening beyond 10,000 years, such screening should be based on the NID concept for these long time frames. When using this tool, it is likely that no additional FEPs are required to be included beyond those DOE has already included in their analyses for the first 10,000 years after repository closure. Maintaining the FEPs screening already used for the first 10,000 years is conservative in the sense of being overly inclusive, but unlikely to affect the mean dose estimates.

Finally, this report provides a general discussion about appropriate individual dose limits for the very far future. While arguments about intergenerational equity are prevalent, there are also counterarguments that suggest the cost to the present-day generation to provide a very stringent level of protection to future generations may also be inequitable. Both US regulation and international guidance is cited in which individual dose levels higher than 15 mrem/yr are considered protective of human health.

Another issue related to an appropriate dose limit in the very far future is that of dose apportionment. Both national and international regulatory bodies recognize that a dose limit from all man-made sources of radioactivity in the same range as background doses is reasonable. For most areas of the world, background doses are in the 10^{2} per year range. The concept of dose apportionment is that there are likely to be several man-made sources of radioactivity such that the dose limit for any single activity would need to be set at a fraction of the entire man-made limit. However, in the very far future, the elimination of or enhanced protections from other sources of man-made radioactivity in the Yucca Mountain region may result in such an apportionment becoming no longer be necessary.

The recommendations made in this report are summarized as follows:

- Because the court rejected all challenges to the existing regulations governing the first 10,000 years, EPA should take a surgical approach to revising its standard: specifying beyond 10,000 year requirements as separate, stand-alone, provisions that do not alter what is required regarding the first 10,000 years;
- A change of approach to the regulation and its implementation should be adopted for those provisions of the regulation that will address time frames beyond 10,000 years if the regulation, as a whole, is to remain implementable;
- The use of a “stylized” approach for scenario identification and level of rigor in the models should be established by the NRC for time periods beyond 10,000 years;
- Future climate states should be fixed by rulemaking to one or, at most, two: present-day “interglacial” and “glacial;” if a “glacial” climate state is specified, the regulation should also specify a set of assumptions to govern human behavior that is consistent with the way humans would be expected to live in such a climate. However, it is preferable to simply assume the present-day interglacial climate state continues for the entire compliance period since it is likely to be reasonably bounding and the most implementable;

- No additional FEPs screening is required for the time period beyond 10,000 years. This is because the current FEPs screening criterion (FEPs with a probability lower than approximately 10^{-8} per year can be screened out) is already overly inclusive compared to the approach recommended by the TYMS panel. If additional FEPs screening beyond 10,000 years is required by EPA, the concept of negligible incremental dose should be used as a screening tool; and
- A two-tiered dose limit should be specified: one level for the first 10,000 years; and a second, higher level consistent with the increased uncertainty should be used for the period beyond 10,000 years.

EPRI seeks feedback from all interested parties on the content and recommendations made in this interim report.

ACKNOWLEDGMENTS

EPRI would like to gratefully acknowledge the efforts of:

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INTRODUCTION

This report has been developed to address the possible ramifications of the July 9, 2004 decision by the US Court of Appeals, District of Columbia Circuit, vacating the provision in regulations 40 CFR 197 and 10 CFR 63 for a regulatory compliance period of 10,000 years for the proposed spent nuclear fuel (SNF) and high-level radioactive waste (HLW) repository at Yucca Mountain, Nevada. The purpose of this report is to consider technical implications and options associated with regulatory compliance periods in excess of 10,000 years that:

- Are consistent with the Court ruling;
- Result in a "meaningful" standard that protects public health and safety in a constructive and equitable manner; and
- Would be "reasonable" and implementable in a regulatory environment.

Issues associated with the Court ruling have arisen because deep geologic disposal, combined with a robust engineering design, cause peak individual doses to be delayed for very long periods of time. A combination of an extremely long time frame for performance with a peak dose criterion could, therefore, ironically but logically drive DOE to the use of a less robust engineered barrier system, which would fail at times less than 10,000 years when the uncertainties in the state of the system are less than at later times. The reason to raise this point is not to suggest DOE should select a less robust EBS design. Rather, it should be recognized that doses arising in the far distant future are a representative characteristic of a good site and repository design. In carrying out analyses to peak dose, the regulatory structure should be established in a way that recognizes this fact, and which does not make compliance assessments for a good site and design more onerous than for a less robust system.

The report is organized as follows. Chapter 1 provides the legal, regulatory, and technical background leading to the court decision and other relevant information to support the discussion in the following chapters. Chapter 1 includes a summary of the important laws, development of the existing regulations, and the highlights of the recommendations made by the National Academy of Sciences (NAS) panel on the Technical Bases for Yucca Mountain Standards (TYMS) in its 1995 report (TYMS, 1995). Chapter 2 discusses the elements of a regulation that make it "meaningful" over a long period of time – a recommendation made in TYMS (1995). In Chapter 3, the features of the uncertainty that increase at Yucca Mountain are elaborated. Climate change presents special issues for time periods beyond 10,000 years, and is discussed in Chapter 4 (and Appendix A). International concepts on how to deal with the issues associated with long time frames are presented in Chapter 5. In Chapter 6, a series of options are considered for a revised standard consistent with the July 9, 2004 US Court of Appeals ruling. The proposed options are evaluated to determine if they are "based upon and consistent with" the 1995 TYMS panel recommendations (TYMS, 1995) and meet the other requirements listed in the three bullets above. These options are summarized and harmonized, and recommendations are made in Chapter 7. A brief summary of the final recommendations is provided in Chapter 8.

1.1 Legal and Regulatory Background

The Nuclear Waste Policy Act of 1982 (NWPA, Pub. L. 97-425) and subsequent amendments in 1987 and 1992 (Energy Policy Act) formalized the current Federal program for the disposal of SNF and HLW by:

1. Making the US Department of Energy (DOE) responsible for siting, building, and operating an underground geologic repository for the disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW);
2. Directing the US Environmental Protection Agency (EPA) to set applicable environmental radiation protection standards based upon authority established under other laws; and
3. Requiring the US Nuclear Regulatory Commission (NRC) to implement the EPA standards by incorporating them into its licensing requirements for the Yucca Mountain repository.

In the 1992 Energy Policy Act (EnPA), Congress directed EPA to promulgate a "reasonable" standard for individuals and only individuals. Section 801 of the Act specifically directed EPA to:

> "…promulgate, by rule, public health and safety standards for protection of the public from releases from radioactive materials stored or disposed of in the repository at the Yucca Mountain site. Such standards shall prescribe the maximum annual effective dose equivalent to individual members of the public from releases to the accessible environment…"

The EPA issued its first regulation for disposal of HLW in 1985 as 40 CFR 191. At the time, this regulation applied to any proposed deep geological disposal facility. Subsequently, NRC issued 10 CFR 60 to address its regulatory responsibility for geological disposal of commercially generated HLW under NRC jurisdiction. In 1987, the US Court of Appeals remanded 40 CFR 191 for reconsideration of several provisions of the rule. These provisions were associated with the application of Safe Drinking Water Act standards to groundwater at Yucca Mountain, the first time drinking water standards had been applied to untreated groundwater. EPA had still not reissued the regulation when Congress passed the Energy Policy Act of 1992 (EnPA), which, in Section 801, established a separate regulatory process for a repository at Yucca Mountain. In 1993, EPA reissued 40 CFR 191 to address the Court's concerns, but this regulation no longer applies to Yucca Mountain. 40 CFR 191 establishes the standards used for the Waste Isolation Pilot Plant (WIPP) in New Mexico, and would apply to any potential future geological repository not at Yucca Mountain. Similarly, 10 CFR 60 would apply to any future geological repository not at Yucca Mountain for which NRC has regulatory authority.[1] Both 40 CFR 191 and 10 CFR 60 establish a regulatory period of interest of 10,000 years and derived release limit standards.

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[1] NRC has no jurisdiction over WIPP, so 10 CFR 60 is not currently in use for any specific disposal facility. Instead, EPA issued 40 CFR 194 as the regulation implementing 40 CFR 191 for WIPP. EPA exercises direct regulatory authority over WIPP.

In addition to severing Yucca Mountain from 40 CFR 191, EnPA stipulated that EPA should arrange for the National Academy of Sciences to make recommendations on the scientific basis of a new Yucca Mountain-specific regulatory standard. The House of Representatives Conference Report accompanying the EnPA also requests that the standard be "reasonable" (House of Representatives, 1992). EPA was directed by Congress to develop a new regulation "…based upon and consistent with the findings and recommendations of the National Academy of Sciences…" (EnPA, 1992). The National Academy of Sciences subsequently issued the requested report in 1995 (TYMS, 1995).

While the TYMS (1995) report makes many comments and recommendations regarding the technical bases for Yucca Mountain standards, it is the following recommendation that is the primary subject of this report:

> "The current EPA standard [40 CFR 191] contains a time limit of 10,000 years for the purpose of assessing compliance. We find that there is no scientific basis for limiting the time period of an individual-risk standard in this way. We believe that compliance assessment is feasible for most physical and geologic aspects of repository performance on the time scale of the long-term stability of the fundamental geologic regime – a time scale that is on the order of 10^6 years at Yucca Mountain – and that at least some potentially important exposures might not occur until after several hundred thousand years. For these reasons, we recommend that compliance assessment be conducted for the time when the greatest risk occurs, within the limits imposed by long-term stability of the geologic environment." (pp. 6-7)

In 2001, EPA and NRC issued 40 CFR 197 and 10 CFR 63, respectively, establishing the standards for a repository at Yucca Mountain. Upon issuance of these regulations, DOE began the process of moving toward developing a license application for the Yucca Mountain repository.

In promulgating 40 CFR 197, EPA elected to maintain the 10,000-year compliance period for a variety of technical and policy reasons. EPA (66 FR 32132) stated that they considered two options in developing 40 CFR 197: calculations to peak dose and calculations out to a fixed time. In restricting the analyses for demonstration of compliance to 10,000 years, EPA recognized that "because of the inherent uncertainties associated with such long-term projections, [the analyses] are not likely to be of the quality necessary to support regulatory decisions..." In fact, TYMS (1995) noted that EPA may well have policy reasons for selecting an alternate time period (TYMS, pg. 19). The primary policy decision cited by EPA in justifying the 10,000 year cutoff was that "the uncertainties in compliance assessment become unacceptably large..." and referred to consistency with earlier arguments made in developing 40 CFR 191 (50 FR 38076).

Soon after the issuance of 40 CFR 197 and 10 CFR 63, thirteen legal challenges were filed against EPA, NRC, DOE, and other United States Government entities challenging various aspects of their regulations, along with some other parts of the Yucca Mountain decision-making process not discussed in this report. Among the challenges was that EPA improperly selected a compliance time frame of 10,000 years because it was not "based upon and consistent with" the TYMS (1995) recommendations.[2] These legal challenges were consolidated into a single court

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[2] A total of 16 issues derived from these 13 lawsuits were listed by the Court as challenging various aspects of the Yucca Mountain repository. The EPA standard was challenged by the State of Nevada, the Nuclear Energy Institute,

case before the District of Columbia Circuit, US Court of Appeals, which was decided on July 9, 2004 (DC Circuit Court of Appeals, 2004). All of the challenges to the regulations were struck down except one feature of the EPA's regulation. This feature was the provision in 40 CFR 197, and the derivative provision in 10 CFR 63, to limit comparison with dose standards to the first 10,000 years of the lifetime of the disposal facility. Even here, the Court stated that its reasoning was based on the legal basis for the regulation: EPA had not, in their estimation, provided an adequate explanation of why they deviated from the recommendations of the National Academy of Sciences regarding the established time period. The Court did not question the protectiveness of the 10,000-year period.

In vacating this portion of the regulations, the Court has directed EPA to "either issue a revised standard that is 'based upon and consistent with' NAS's finding and recommendations or return to Congress and seek legislative authority to deviate from the NAS Report." (DC Circuit Court of Appeals, 2004, pg. 31)

This report has been written to address the technical implications of the Court's ruling assuming no legislative action is taken responsive to the decision. While some policy implications are also addressed, it is only to the extent that technical features provide insight into possible policy approaches.

1.2 National Academy of Sciences Positions

The issues of relevance to time frame evaluated by the National Academy of Sciences (NAS) Committee on the Technical Bases for Yucca Mountain Standards (the "TYMS" Committee) are summarized in this section, with supporting citations and rationales from TYMS (1995).

One of the major aspects of the TYMS Committee recommendations was that the standard should be in a form that directly addresses human health. While the TYMS Committee briefly considered other forms for the standard in its report, it argued that the most meaningful standard was one in terms of human health. The primary alternative considered by TYMS was the use of "technology-based standards," along the lines of the subsystem requirements established in 10 CFR 60. TYMS rejected such standards, primarily because they recognized that it is the total system behavior that matters to safety, and that application of subsystem requirements might "foreclose design options that ensure the best long-term repository performance." (TYMS, pg. 77)

As discussed in TYMS (1995), a standard whose measure of safety is individual health risk requires that the habits of the hypothetical individual, and the hypothetical community in which the individual lives, need to be described in sufficient detail so that health risk estimates can be made.

The essential point to be addressed when considering how to establish a meaningful regulatory construct for any time period was succinctly stated by TYMS (1995):

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and others. The NRC was challenged by the State of Nevada on several issues. Nevada also sued the US government over a constitutional issue and DOE over the Site Recommendation process. Of these 16 issues, only the ruling regarding the time frame of compliance was in favor of the plaintiff.

> "… standards are useful only if it is possible to make meaningful assessments of future repository performance with which the standards can be compared…Doing so, however, requires using the rulemaking process to arrive at a regulatory decision about certain assumptions as part of the standard, for example, about future human behavior." (pg. 21)

It is worth noting that TYMS (1995) considers that meaningful assessments are best accomplished by analyses of individual health risk, which requires specification of exposure scenarios, which must be applied into the future of the repository:

> "We recommend the use of a standard that sets a limit on the risk to individuals of adverse health effects from releases from the repository…It is essential to define specifically how to calculate this risk… The first step in calculating risk is therefore to develop a distribution of doses received by individuals, taking into account all of the events that go into determining whether a dose is received…" (pg. 42)

EPA established its regulation based on a number of factors, including policy decisions, consistent with its policy decision to limit the regulatory compliance period to 10,000 years. With that aspect of the regulation overturned, it is now necessary to identify which assumptions should be established by rulemaking, and which should be included as part of the formal safety analysis, given a compliance time period greater than 10,000 years.

While TYMS (1995) indicates a preference for individual health risk modeling to the time of peak release, this recommendation is predicated on the following: *"Selection of a time scale for the standard must therefore take into account the scientific basis for the performance assessment."* (pg. 30), while at the same time acknowledging that uncertainties, such as those in future human behavior, limit the basis for risk-based analysis.

All other aspects of the existing EPA and NRC regulations for Yucca Mountain were either not challenged in the courts or were upheld in the Court of Appeals ruling.

Other details of the TYMS Committee recommendations are discussed in subsequent sections of this report.

2

TREATMENT OF UNCERTAINTIES OVER VERY LONG TIME PERIODS AT YUCCA MOUNTAIN

As discussed briefly in the previous chapter, the TYMS Committee recommended that the time period of compliance for Yucca Mountain might be as long as one million years. The TYMS Committee based this recommendation partially on their reliance on the perceived time period of physical and geologic process "stability." This chapter discusses the TYMS recommendations and additional considerations regarding how to deal with the varying degrees of uncertainty in different features, events, and processes (FEPs) required to make very long-range estimates of individual health or dose risks.

Time scales to be considered in compliance assessments are strongly influenced by a number of factors. Among these factors are:

- longevity of the hazard of the waste,
- longevity of engineered barrier systems,
- duration of geological stability,
- duration of surface environment stability, and
- changes in human behavior.

Each of these factors is influenced to differing degrees and in differing ways by external events and processes that may act on the disposal system. Key external events and processes that are considered in compliance assessments for Yucca Mountain include:

- igneous events,
- seismicity, and
- climate change

It is necessary to distinguish between external events and processes that are "unknowable" (e.g., future human behavior) with those that are not known "in detail," but are still "boundable." The time dependence for four parts of a repository system is shown in Figure 2-1. Any viable revised regulatory standard to assess peak health effects must consider the differences in time-dependent behavior of these four parts of a repository system, to be consistent with the recommendations of the TYMS (1995) report. Changes in each of these spatial components occur over differing time frames:

- human lifestyle,
- the surface environment,

- the deep geosphere of the Earth, and
- the engineered barrier system (EBS).

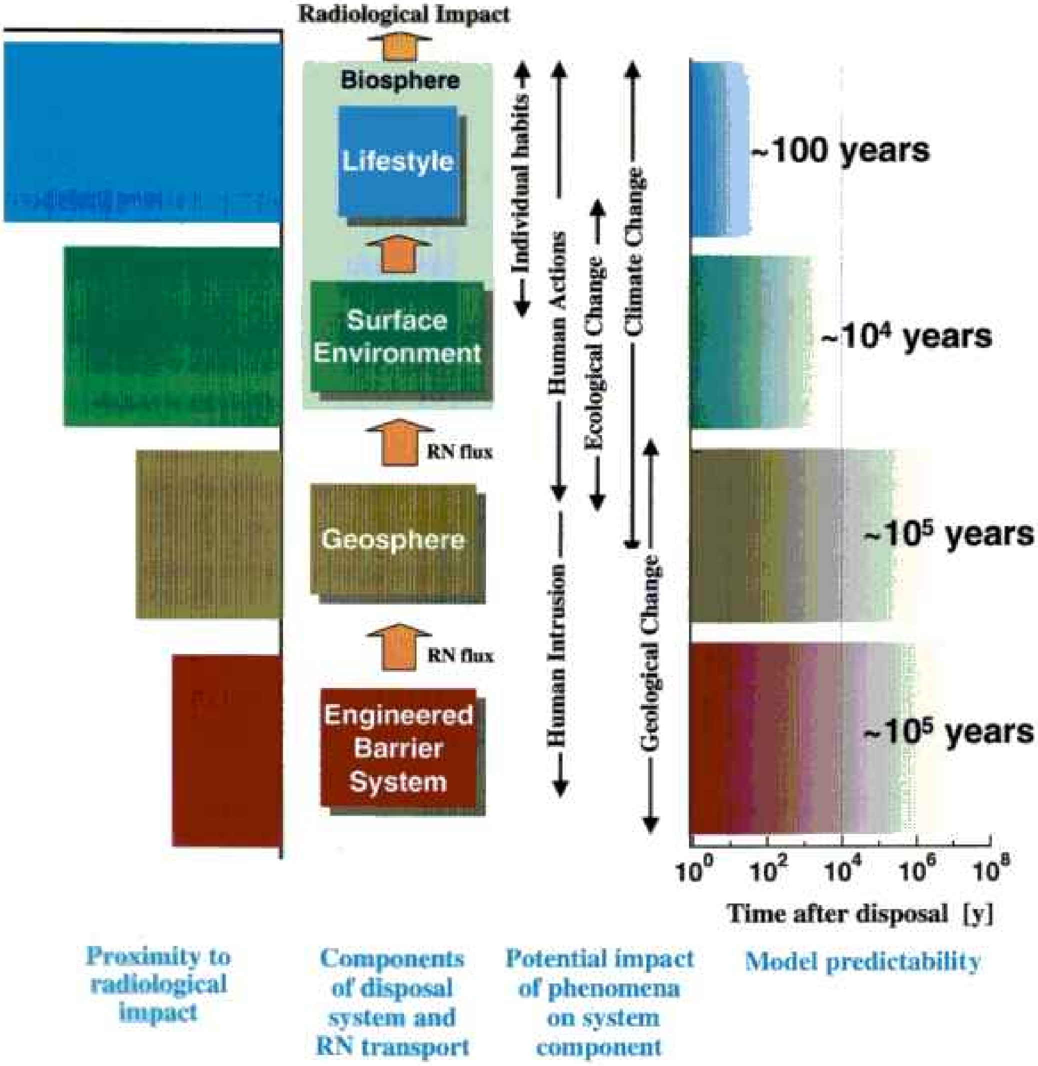

Figure 2-1
Comparison of time dependence and model predictability for various parts of a repository system (Masuda, 2004).

The time-dependent behaviors of each of these components are fundamentally different, responding in different manners to potential perturbing processes such as climate change, geological change, and human activities.

Furthermore, the hydrologic behavior of the system is influenced by all of these components, plus at least one of the external FEPs: climate. If one considers the use of groundwater by humans as part of the relevant hydrologic behavior of the system, then it can be seen that the hydrologic response also has a time-dependence and predictability on a wide range of time scales.

2.1 Most Physical and Geologic Processes are Comparatively "Stable" and "Quantifiable"

TYMS (1995) touted physical and geological stability as the primary basis for their recommended time scales:

> "We believe that compliance assessment is feasible for most physical and geologic aspects of repository performance in the time scale of the long-term stability of the fundamental geologic regime – a time scale that is on the order of 10^6 years at Yucca Mountain… (pg. 6)"

Then again on page 9, TYMS (1995) states,

> "We conclude that these physical and geological processes are sufficiently quantifiable and the related uncertainties sufficiently boundable that the performance can be assessed over time frames during which the geological system is relatively stable or varies in a boundable manner. The geologic record suggests that this time frame is on the order of 10^6 years…**Once an exposure scenario has been adopted, performance assessment calculations can be carried out with a degree of uncertainty comparable to the uncertainty associated with geologic processes and engineered systems.**" (emphasis added)

Thus, the TYMS Committee recommends that the approach to dealing with FEPs that are less certain than those for physical and geologic processes is to "bound" those larger uncertainties. As is discussed later in this report, TYMS clearly indicates that one way of bounding uncertainties is via rulemaking.

TYMS (1995) considered the geological aspects of the system to be "substantially different" than the other aspects of the system. TYMS (1995) illustrated this difference by focusing on the unpredictability of the details of human activities:

> "We then consider the scientific basis for making an assessment of Yucca Mountain. We have found it useful to separate this evaluation into two parts, one dealing with the physical properties and geologic processes relevant to the behavior of the wastes and the other with those aspects of performance assessment that deal with assumptions about where and how people live, how they might be exposed through the food and water they consume and other factors that could affect exposures to radioactive wastes. We shall refer to this latter collection of factors that must be considered as exposure scenarios. The reason for separating these two elements of performance assessment is that **the nature of calculations in each is substantially different."** (TYMS, 1995, pg. 69) [emphasis added]

2.1.1 Geosphere

The geosphere, in the usual context for geological disposal, refers to the deep geological environment, greater than a few tens of meters below the ground surface. Over geological time scales of 100,000 years or longer, the geosphere of a repository site will be mechanically and chemically stable. The fundamental concept of geological disposal of radioactive waste is to use the known stability of geological systems to advantage in the isolation of wastes. ”Geological stability” is interpreted to mean that the site should not experience dramatic and unpredictable morphological changes over the time period of concern for the performance assessment.

After many years of study, the consensus of scientific views is that the geosphere of the Yucca Mountain system is indeed stable and can be relied upon to isolate emplaced wastes (see, e.g., NAS, 1990). Furthermore, since it is relatively isolated from near-surface phenomena, the geosphere remains relatively unperturbed by major boundary conditions. Among these boundary conditions is climate change, which affects the repository primarily by changes in infiltration rate at the repository horizon. Climate change therefore may have a direct effect on the hydrosphere, while leaving the geological stability intact. However, as is discussed in Appendix A, there remains considerable uncertainty about the effect of climate change on the hydrosphere, from uncertainty in the response of infiltration rate to the response of saturated-zone flow.

For the analysis of the total system performance, however, the geosphere must be considered in a broader sense than just the deep environment of the repository. Pathways between the repository and humans inevitably include portions of the geosphere that are closer to the surface, hence more susceptible to long-term changes. To a large extent the changes to the near-surface environment are linked closely to changes in climate. Hence, elements of the geosphere important to TSPA (e.g., groundwater flow) are subject to change and uncertainty over very long time periods.

2.1.2 Other Physical Processes

As described above, the TYMS panel noted that, in addition to geologic processes, “most physical processes” are “quantifiable and the related uncertainties sufficiently boundable.” Pages 85 to 90 of TYMS (1995) provide a brief discussion of the nature of these processes. Many of the processes discussed relate to the engineered barrier system (EBS).

In terms of the long-term behavior of the EBS located at depth within a stable geologic formation, the most quantifiable parameters are the half-lives of the radionuclides in the wastes and their consequent heat output. Consideration of typical activity and radiotoxicity curves for spent fuel leads to identification of two important points in time related to the long-term, safe isolation of nuclear waste in geologic repositories.

The first point in time is associated with the decay of the short lived, hence highly active, radionuclides like Cs-137 and Sr-90, with half-lives on the order of several tens of years. Containment times on the order of 10^3 years (i.e., for any specific nuclide, isolation for longer than 10 half lives leads to a 1000-fold reduction in activity) ensure that such shorter-lived, heat-producing nuclides have essentially decayed. Hence after this point in time, the associated transient thermal pulse within the EBS and surrounding host rock is past.

At longer times, the decay of longer-lived nuclides remaining in the waste is more gradual. A second point in time can be linked to when the radioactivity, or radiotoxicity (see Figure 2-2), of the spent fuel in the repository, still located many hundreds of meters beneath the ground surface, equals the radiotoxicity of the original uranium ore used to produce the fuel. Calculations of the time this point is reached can differ depending on the normalization assumed (e.g., mass vs. volume, activity vs. radiotoxicity, etc.). NAS (1983) posed this point in terms of an equivalent dilution volume, and calculated the results presented in Figure 2-3. There is clearly some variation in the point at which the crossover between fuel and ore occurs, but 10,000-300,000 years is a representative and justifiable range.

Responses of the engineered barrier system to major external events and processes are minimal. This, indeed, is a significant part of the design strategy for Yucca Mountain. The robust materials used in the waste package design are able to withstand conditions during an igneous event (EPRI, 2004a), in the aftermath of an igneous event (EPRI, 2004b), or in response to changes in infiltration associated with climate change (EPRI, 2003). Consequently, the engineered barrier system can be considered to be stable and, to a degree, predictable in its behavior over very long time periods.

Yet the TYMS Committee provides little to no guidance on how much uncertainty is associated with geologic and "most physical" processes over one million years – a level of uncertainty that the TYMS Committee finds acceptable. TYMS states that

> "Detailed estimates of time for canister failure are less important for much longer-term estimates of individual dose or risk. (p 85)."

This statement is inconsistent with current thinking and does not reflect the present expectation of the behavior and importance of the engineered barrier system at times greater than 10,000 years. Uncertainties associated with the waste package failure rate form a significant part of the difficulty in implementing the TYMS recommendations. The reality of the results of TSPAs carried out by DOE, NRC, and EPRI shows that the peak dose is strongly dependent on the timing and rate of failure of waste packages, as well as on the detailed physical and chemical processes accounted for in the near-field of the repository.

TYMS (1995) notes on page 86 that:

> "[f]urther refinements in release-rate predictions can be made *if* the time-dependent failure characteristics of waste containers and of Zircaloy cladding on spent fuel can be estimated." (emphasis added)

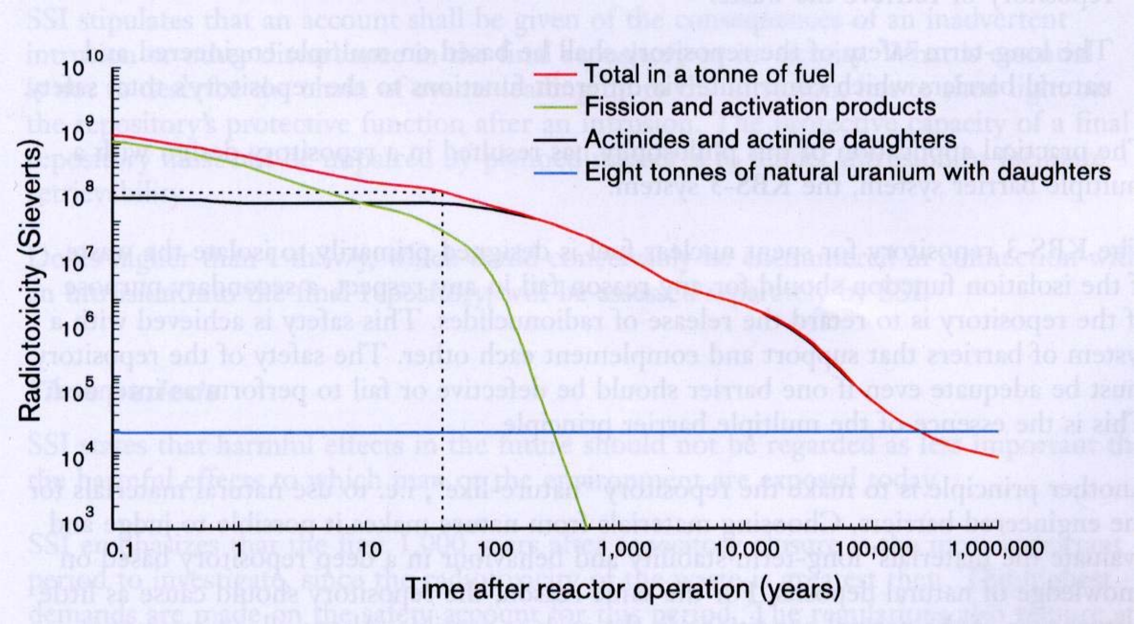

Figure 2-2
Radiotoxicity of spent fuel as a function of time after discharge from the reactor for Swedish BWR fuel with a burnup of 38 MWd/tU. Radiotoxicity pertains to ingestion via food. From Figure 1-2 of SKB (1999).

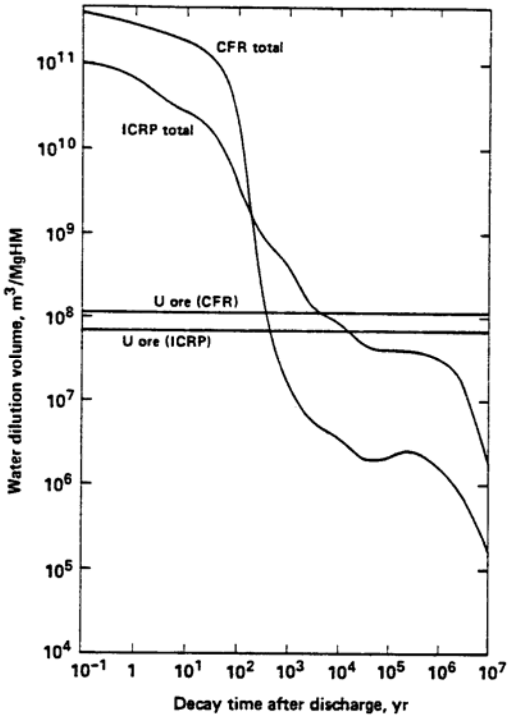

Figure 2-3
Equivalent toxicity comparison between spent fuel and uranium ore, for two sets of dose conversion factors (Excerpted from NAS, 1983).

The next few paragraphs summarize approaches taken to refining time-dependent failure characteristics since the issuance of TYMS (1995). Many have noted that the combination of uncertainties in estimating waste package failure rates and groundwater flow past failed waste packages can have a significant effect on peak dose estimates.

The prediction of waste package lifetimes is treated probabilistically in both the IMARC (EPRI) and WAPDEG (DOE) performance assessment models. Probabilistic waste package degradation models are used to account for the variability and uncertainty in the conceptual models and the values of various input parameters. Although the detailed conceptual models used by EPRI and the DOE differ in some respects, both IMARC and WAPDEG take into account the possibility of waste package failure due to general corrosion (GC), localized corrosion (LC), and stress corrosion cracking (SCC).

In the IMARC code, it is predicted that waste packages will remain intact for 80,000 yrs to $>10^6$ years, with 98.5% of failures resulting from GC of the shell of the waste package. This spread in failure times is a result of the variation in the waste package environment (primarily the temperature in the current version of the code) and uncertainty in various model parameters (e.g., the mean rate of GC at a given temperature) (EPRI, 1998).

The WAPDEG code treats the effects of uncertainty differently, generating separate cumulative failure distributions for the mean, upper, and lower bounds, as well as for intermediate confidence intervals. For the conservative (low probability) upper bound prediction, the first waste package failure occurs after 120,000 yrs, with 50% of waste packages failing by 310,000 yrs, and 100% failing by 500,000 yrs. Waste package failure in this scenario is primarily a result of SCC (DOE, 2000).

TYMS (1995) also notes that

> “…the uncertainties about cumulative releases to the biosphere that depend on the rate of failure of the waste packages are large in the near term but are smaller later, when enough time has passed that all of the packages will have failed.” (pg. 19)

This quote, while technically correct, appears to be inconsistent with the main line of argument set out by TYMS, that the regulation should be based on *peak* dose. The uncertainty associated with *cumulative releases* to the biosphere resulting from rate of failure of waste packages does indeed decrease with time once they have all failed, but the uncertainty in *peak dose* is directly related to the uncertainty in the *rate* of failure of waste packages. The farther out in time that the waste packages remain intact, the greater the uncertainty about the conditions in which they exist, and therefore the greater the uncertainty in the failure rate of waste packages, and its associated effect on uncertainty in peak dose (see Section 3.2.2). Thus, the “near term” referenced by the TYMS panel in the quote above extends all the way to the time of peak dose. Given the very long lifetime of the waste packages, the TYMS concept of “near term” is now very long, indeed.[3]

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[3] At the time, TYMS (1995) estimated waste package lifetimes were much shorter than that provided by the current DOE design.

The combination of an extremely long time frame for performance with a peak dose criterion could, therefore, ironically but logically drive DOE to the use of a less robust engineered barrier system, which would fail at times less than 10,000 years when the uncertainties in the state of the system are less than at later times. The reason to raise this point is not to suggest DOE should select a less robust EBS design. Rather, it should be recognized that doses arising in the far distant future are a representative characteristic of a good site and repository design. *In carrying out analyses to peak dose, the regulatory structure should be established in a way that recognizes this fact, and which does not make compliance assessments for a good site and design more onerous than for a less robust system.*

Overall, TYMS provides little discussion of the behavior of the "physical" system at long times, focusing attention instead on geological processes. Indeed, TYMS includes only a few comments related to the engineered barrier system suggesting that further work by DOE may show insensitivity of release rate to infiltration rate (p. 85) and that improved credit for cladding might be possible (p. 85).

2.2 Assessing Future Human Behavior is Scientifically Intractable and No Predictions about it Can be Made

There is general consensus in the waste management literature that science cannot address potential future changes in human behavior. This consensus is reflected in the TYMS (1995) report, in existing US regulations, and in the international literature. For example, a key feature of the TYMS (1995) findings is how to develop a standard that does not require more scientific information than is possible to reasonably obtain. This issue is summarized in the following paragraph:

> "There are several choices to be made in designing the standard for which science cannot provide all the necessary guidance – defining the critical group to be protected or the radionuclide pathways to them through the biosphere for example. Since these choices must be made, even in the absence of clear-cut scientific information, we recommend that such issues should be treated as part of the rulemaking process, since this process … allows a broader scope for discussing and weighing alternatives." (pg. 31)

Details of the way the international community addresses this issue are discussed in Chapter 5.

The TYMS (1995) primary example of an issue lacking sufficient scientific information is the basis for establishing human behavior and exposure scenarios:

> "Specifying exposure scenarios therefore requires a policy decision that is appropriately made in a rulemaking process conducted by EPA." (pg. 10)

TYMS (1995) elaborates on this specific issue further:

> "…it is not possible to predict on the basis of scientific analyses the societal factors required for an exposure scenario. Specifying exposure scenarios therefore requires a policy decision that is appropriately made in a rulemaking process conducted by EPA." (pp. 9-10)

Once the exposure scenario is established by rulemaking, TYMS (1995) asserts that

> "…performance assessment calculations can be carried out with a degree of uncertainty comparable to the uncertainty associated with geologic processes and engineered systems." (pg. 9)

That is, since TYMS (1995) stated that a "meaningful assessment" should be directly linked to individual risk, and since individual risk analysis requires specifying an exposure scenario, TYMS implies that fixing the exposure analysis in rulemaking allows for a "meaningful assessment" in cases where uncertainties in future "system" behavior are large or unknowable.

The TYMS (1995) report makes a number of statements on this issue.

> "Based upon our review of the literature, we conclude, however, that it is not possible to predict on the basis of scientific analyses the societal factors required for an exposure scenario. Specifying exposure scenarios therefore requires a policy decision that is appropriately made in a rulemaking process conducted by EPA…Additionally, EPA should rely on the guidance of ICRP that the critical group be defined using present-day knowledge with cautious, but reasonable, assumptions." (pp. 9-10)
>
> "Projecting the behavior of human society over very long periods, for example, are beyond the limits of scientific analysis…policy judgments are required." (pg. 20)
>
> "In the case of human activity...there is no scientific basis for prediction of future states and the limit of our ability to extrapolate with reasonable confidence is measured in decades, or at most, a few hundred years…" (pp. 54-55)

The implication of these quotes is clearly that the detailed characteristics of potential future human behavior needed to identify and quantify the exposure scenarios leading to individual health risk should be established in a rulemaking proceeding. EPA clearly adopted this position in the promulgation of 40 CFR 197.

TYMS (1995) went on to conclude that factors important in establishing the exposure scenario should be established by regulatory policy. They carried that argument further by stating that the regulatory compliance period should be based on the stability of the majority of the physical and geologic processes of the site. In doing so, they made a logical link that the compliance assessment is constituted only of the engineering and geological component on the one hand, and of the exposure assessment component on the other. They then established that the human behavior should be fixed to current day conditions using rulemaking, imputing that by fixing human behavior, the uncertainties in the exposure assessment would be fixed. Based on these logical links, TYMS (1995) concluded that the geological and engineering functions could be extrapolated to time frames on the order of 10^6 years. In this report, the appropriateness of that link is explored to provide recommendations regarding what parts of the analysis should be established by policy and what parts should be evaluated in the compliance assessment. Current concepts in TSPA call for parts of the analysis to be treated in a stylized manner, when they are not predictable "in detail" (see Section 3.1 and Chapter 5).

In order to calculate individual health risks from a repository, it is necessary to know both human physiology and human behavior. Human physiology, while it has evolved somewhat over the past hundred thousand years or so, has probably remained fairly stable. The field of health physics studies the interaction of radiation with human physiology. While recent advancements have been made in the understanding of the details of the interaction of radiation with humans, there are still uncertainties related to the uptake of specific radionuclides into the body, and the absorbed dose. However, it is felt that this aspect of calculating individual health risks is sufficiently subject to scientific analysis to be included in a very long-term regulatory standard. In fact, this is the second component of calculating overall dose (or health risk) that the TYMS Committee indirectly recommended be fixed by rulemaking in suggesting a standard set of health physics conversions (e.g., ICRP) be used. In essence, by adopting single-valued conversions between radionuclide uptake and dose or health risk, the TYMS Committee recommended that uncertainties in the health physics parameters not be included in the compliance assessment either. While the TYMS Committee noted that its recommendation of the use of health risk allowed future updates on the dose-to-health risk conversion factors based on new data, the TYMS Committee did not specifically recommend a direct incorporation of the underlying uncertainties into the compliance assessment.

The human activities at a given site, however, are the most rapidly changing part of the overall repository system for which individual health risk (or dose) projections are required. Based on observations of past human behavior, it is generally acknowledged that human behavior is unpredictable over a time period of a few decades (ICRP, 2000; BIOMASS, 1999; BIOCLIM, 2003).

However, it is useful to make the distinction that this degree of unpredictability relates to the *details* of human activities, denoted *human habits* in Figure 2-1. Since the onset of the agricultural revolution several thousands of years ago,[4] lifestyles have centered on the use of agriculturally derived meats, grains, vegetables, and fruits. Indeed, it could be argued that the main features of food consumption have remained approximately constant since then; changes over this longer time frame are denoted *human actions* in Figure 2-1. It is in the details (habits) that things have changed. Similarly, changes since the industrial revolution have made changes in the details of how people spend their time: toward sedentary pursuits and away from farming. However, these changes have not broadly changed the overall types of activities in which people are engaged.

Despite rapid changes in the details of how food and drink is produced and consumed, people still need food and drink and they are still produced (to some extent) using local natural resources. However, to calculate individual health risk (or dose), as TYMS (1995) requires, it is necessary to make detailed assumptions about the “where” and “how” and “how much” regarding food production and consumption. This delineates the differences between the known and the unknown about future behavior patterns.

One major aspect of human habit uncertainty is related to human action differences under differing climates. For example, present-day behavior in the Yucca Mountain region is largely governed by the generally hot, arid climate state that exists today. Use of groundwater, even the types of crops that can be grown are largely governed by the climate state. Agricultural practices

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[4] In many parts of the world, the agricultural revolution occurred before recorded history. Archeological evidence suggests that it began much more recently among indigenous peoples in the United States (see, e.g., Diamond, 1997). Regardless of when it began, at this stage, peoples move from a predominantly hunter-gatherer lifestyle to a predominantly agrarian one.

and other human habits will *necessarily* change if Yucca Mountain undergoes significant future climate changes (BIOMOVS, 1996; BIOCLIM, 2003). That is, it would not be reasonable to assume the same behavior that is exhibited in the Yucca Mountain region today would represent behavior for a much cooler, wetter climate in the future at Yucca Mountain. This imposes a difficulty in reconciling the dependency of human behavior on climate. This will be addressed in Chapter 4 and Appendix A.

2.3 Consideration of Other Uncertainties

TYMS (1995) indicated that:

> Several gradual and episodic natural processes, specifically global-climate change, volcanic eruptions, and seismic activity, have the potential to modify the properties of the reservoirs and the processes by which radionuclides are transported through these reservoirs to the biosphere. (p. 51)

Uncertainties in seismic and igneous activity are briefly discussed in the next two subsections. Uncertainties introduced due to climate change are discussed in more detail in Chapter 4 and Appendix A.

EPA requirements on inclusion of events and processes with probability above 10^{-4} over 10,000 years has led DOE to consider seismic and igneous scenarios for disruption of the repository. TYMS (1995) considered the geological regime to be stable, despite the potential occurrence of seismic and igneous events at the repository.

The question arises whether uncertainties in these scenarios increase with time, as do uncertainties in other parts of the TSPA. Extrapolation of data to extreme values of probability of occurrence carries with it an intrinsic degree of uncertainty. Data taken over relatively short periods of time will likely reflect only occurrences that are expected over short recurrence intervals. These data, therefore, can lead to uncertainties in the tails of the distribution, at progressively longer recurrence intervals. Evaluating the tails of such distributions therefore introduces a type of uncertainty that grows with time, since the magnitude of events at long times reflects their recurrence intervals, and projections farther out on the tails of the distribution are more uncertain than those closer in.

2.3.1 Seismic Activity

Bechtel/SAIC (2004) states that the:

> "rate of tectonic deformation since at least the beginning of the Quaternary Period, 1.8 million years ago, is too slow to significantly affect Yucca Mountain during the regulatory compliance period of 10,000 years."

The evaluation considered all rates of slippage along faults occurring in the Quaternary period (Bechtel/SAIC, 2004, pg. 2-20), hence it is based on a data record in excess of the proposed duration of TSPA. In evaluating effects of seismic hazards, Bechtel/SAIC (2004) describes their approach for extrapolating data to low-probability events to be evaluated in TSPA:

> At low annual exceedance probabilities, this leads to computed ground motions that are likely to be physically unrealizable. That is, the computed ground motions produce strains that would cause damage to the rock at the site (which is not observed), thus limiting the level of ground motion that could be propagated. Also, the combinations of seismic source parameter values required to produce such ground motions may be unachievable. Because of these constraints on low-probability ground motions, seismic inputs for postclosure analyses are developed from the PSHA results only for annual exceedance probabilities of 10^{-5}, 10^{-6}, and 10^{-7}. Seismic inputs based on PSHA results with an annual exceedance probability of 10^{-8} are not developed because of the physical limitations on ground motions at Yucca Mountain. Analyses using the developed seismic inputs, in combination with constraints on low probability ground motion at Yucca Mountain, form the basis for evaluating repository performance for seismic events with annual probabilities as low as 10^{-8}.

This approach to estimating the consequences of seismicity would be unaffected by extrapolating out to later times after 10,000 years, since bounding ground motions (up to the physical limits of the system) are already included. Consequently, even though extrapolation of data from the data record to long times introduces a significant scientific uncertainty that grows with time, this uncertainty is being managed for regulatory compliance through the use of bounding assumptions.

2.3.2 Igneous Activity

Similarly, consideration of the probability of occurrence of igneous activity is based primarily on observations of Quaternary eruptions, with older silicic eruptions acknowledged to represent a different tectonic regime than presently exists. These Quaternary eruptions span a longer geological time than one million years, so the change from a 10,000-year compliance period would not influence the fundamental base of knowledge upon which the TSPA is derived. Here, too, the TSPA analysis is acknowledged to be extremely conservative and bounding (EPRI, 2004), so extensions to a longer time of compliance will not adversely affect the DOE's TSPA technical basis.

Furthermore, DOE has presented analyses that indicate the dose due to igneous activity peaks in the first 10,000 years (DOE, 2000). This is due to decay of relatively short-lived radionuclides (primarily Cs-137 and Am-241) that contribute significantly to igneous eruption dose estimates via the inhalation pathway. Thus, extending the time period of compliance to beyond 10,000 years will likely not require any additional treatment beyond the work DOE needed to do to support a 10,000-year compliance period.

2.3.3 Practical Approaches to Dealing with Seismicity, Igneous Activity, and Climate

The TYMS panel recommended two basic approaches to dealing with FEPs that have a greater uncertainty than geologic and some engineered FEPs. TYMS (1995) provides a significant amount of discussion on future human behavior, noting that specifying the necessary details of human behavior for the purpose of calculating individual health (or dose) risk should be done by rulemaking. EPA did, in fact, provide fairly specific guidance on future human behavior in the current version of 40 CFR Part 197, and that guidance was not addressed in the Court's decision.

Among the changes to be addressed in a new regulation is the recognition that the climate will change significantly during the next 10,000 years and that there will be additional significant changes in the period beyond 10,000 years. OCRWM (2000) describes the variation in global climates in the past, and makes the case that similarly large changes are expected in the future in the post-10,000 year period. The probabilities of igneous and seismic events are determined from data ranging over much longer time frames, and as a result estimates of their probabilities do not change in the post-10,000 year period. EPA:

> "...believe[s] that the [Quaternary] Period's duration (approximately two million years) provides an adequate time frame for estimating the frequency and severity of past seismic activity in the repository area. The NAS in its recommendations indicated that the repository area could be assumed to be ''geologically stable'' over a period of one million years for the purpose of bounding natural features, events, and processes. We believe that the Quaternary Period is a sufficiently long period of the geologic record to allow DOE to make reasonable estimates of natural features, events, and processes." (66 FR 32101).

Similarly, EPRI (2004) recommends evaluating "recent volcanism," and defines this as events occurring in the past 10 million years. The shortest period in the geological record of the Yucca Mountain region volcanism is the past 4.6 million years (EPRI, 2004). As a result of the long time period over which these events and processes are evaluated, the evaluation cannot distinguish between probabilities of the events in the first 10,000 years, and the time thereafter.

Consequently, in considering the differences between a 10,000 year standard and greater than 10,000 year standard, climate change is seen to be such that "the nature of calculations" should be "substantially different" from that for geologic aspects. A summary of a broad context for climate change over these time periods is presented in Appendix A.

The time dependence of these components of the TSPA in response to climate change and other external events and processes is reviewed in Chapter 4. The goal is to examine which parts of the analysis are, in the words of TYMS (1995) "sufficiently quantifiable" to be assessed as part of the compliance assessment, and which parts should be treated as part of the "exposure scenario," which TYMS (1995) suggested should be established by rulemaking.

3

THE INCREASE IN UNCERTAINTIES WITH TIME AT YUCCA MOUNTAIN

In this section, the question of whether uncertainties in performance assessment increase with time is addressed, and, if so, whether there are specific times in the future when uncertainties rise more rapidly. For that purpose, it is necessary to review and analyze the evaluation of uncertainties as it is conducted in performance assessment. Before beginning the discussion, it needs to be made clear that performance assessments, which are intended to support regulatory compliance decisions, differ from truly predictive analyses (Kozak, 1994a). As such, the uncertainties and their change in time differ for compliance analyses and predictive analyses (Kozak, 1994; 1994a; 1997). The understanding of the differences between these two concepts grew from the debate in the waste management community in the mid-1990s on "validation" of performance assessment models, culminating in the findings of the INTRAVAL program on model validation (SKI, 1993). At that time, it became generally understood that the ability of performance assessment to predict actual outcomes, even at short times in the future, is rather limited. Kozak (1994) noted that:

> "...the few studies that have conducted post-audits of long-term predictability of contaminant transport have shown generally bad correspondence between predicted and measured contaminant concentrations..."

so that purely scientific analyses lead to large uncertainties even at early times, and that:

> "Model validation, in its usual sense, is unachievable for performance assessment models."

Kozak (1994) went on to note that:

> "...a clear distinction must be made between *scientific* confidence and *regulatory* confidence. Scientific confidence is impossible to achieve for analyses stretching over many thousands of years. On the other hand, regulatory confidence *can* be achieved. Of critical importance is that regulatory confidence is achieved by different mechanisms than is scientific confidence, and that scientific confidence plays an important, but small, role in developing regulatory confidence." [emphasis in original]

The distinction between the two approaches is that a scientific approach seeks to carry out an accurate analysis to predict the future behavior; by contrast, in performance assessment

> "The analyst is not seeking an *accurate* answer, but rather a *range* of possible answers that encompass the current level of uncertainty." [emphasis in original]

As a result of the widespread acceptance of the limits of model validation programs in the mid-1990s, emphasis in the waste management community switched from scientific validation to the concept of developing regulatory confidence in decisions.

A common perception in the waste management literature is that uncertainties in performance assessment results increase with increasing time. Some, however, have countered that uncertainties do not significantly increase in time, and that indeed some uncertainties may decrease in time (see, e.g., TYMS, 1995, pg. 29). At least some of these ideas may evolve from a misinterpretation of the standard approach for plotting performance assessment results on log-log plots. A hypothetical set of TSPA results and their associated parameter uncertainty are shown in Figure 3-1.[5] On a log-log plot, the results give the appearance of uniformity in uncertainty as a function of time.

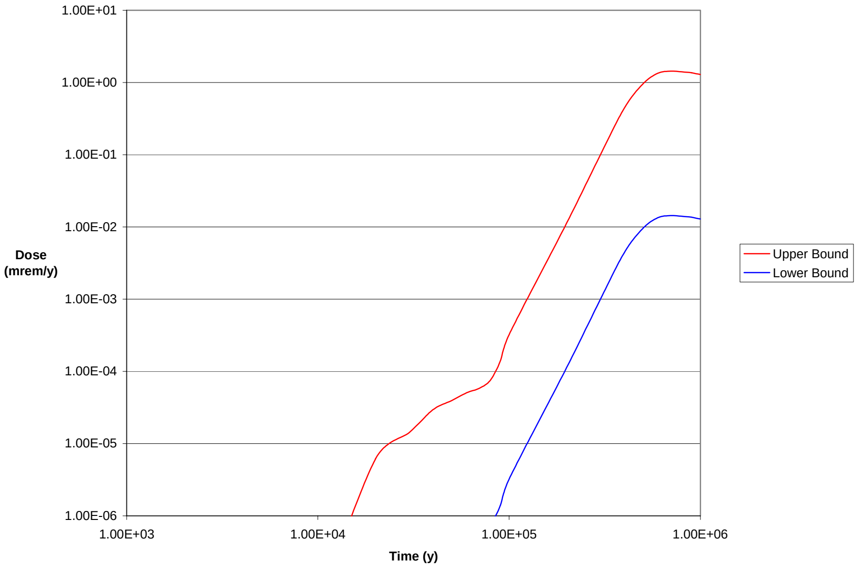

Figure 3-1
TSPA results plotted on a log-log plot. These results show a uniform uncertainty of two orders of magnitude.

However, in the context of compliance analysis, that uniformity is illusory. This illusion is shown in Figure 3-2, which shows the same information on a log-linear scale. In this latter representation, the band of uncertainty clearly grows as the dose approaches its peak value: the value at which regulatory compliance is to be determined. Despite the fact that the uncertainty band contains the same orders of magnitude, the range at smaller dose values is irrelevant to the regulatory decision, and in absolute magnitude is quite small. Similarly, at long times the absolute uncertainty begins to decrease again, as it moves away from the part of the curve important to the decision.

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[5] The upper end of this uncertainty is the total dose generated from IMARC 8.0 (EPRI, 2003). For the purposes of this illustrative example, the lower end of the uncertainty has been set 2 orders of magnitude below that curve.

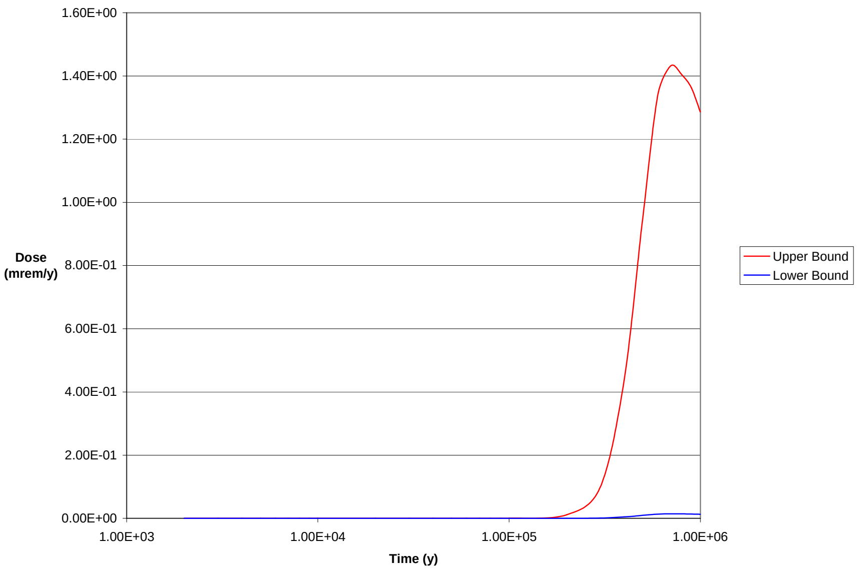

Figure 3-2
The same TSPA results shown in Figure 3-1, but on a log-linear scale.

3.1 Stylized Approaches

Among the most important technical approaches in the literature for dealing with uncertainties at long times is the use of "stylized approaches." Indeed, TYMS (1995) called for the use of a stylized scenario for the human intrusion scenario. This term is found throughout the literature, both in the USA (40 CFR 197, 10 CFR 63) and internationally (NEA, 2002; ICRP, 2000a; IAEA, 2003). Surprisingly, however, there is not a universally accepted definition in the literature of the meaning of this term. Consequently, before addressing the use of stylized approaches, a working definition of stylized approaches is established and described here.

A stylized approach is defined as:

> A set of assumptions established by policy that is used to limit the range of uncertainties considered in the performance assessment, so that the assessment would yield a meaningful test of the ability to protect public health and safety.

Some uncertainties, most prominently those associated with human actions, are accepted to be unquantifiable from a technical perspective. The stylized approach is used to establish bounds on the behavior of people in the future. Stylized approaches are invoked to limit speculation on what might happen in the future, so that the performance assessment may focus on issues that are of greater importance in establishing reasonable assurance of regulatory compliance. So, for instance, EPA has established a stylized approach in establishing the RMEI and the characteristics to be considered in RMEI behavior.

Stylized approaches may also be invoked to limit the FEPs considered in the performance assessment. For instance, TYMS (1995) called for the use of a stylized scenario for inadvertent human intrusion that establishes the processes and exposure pathways to be considered in the scenario. Similarly, a number of European programs consider near-surface processes to be so uncertain in the distant future that they move away from dose or risk criteria to other indirect indicators of system safety (NEA, 2002; IAEA, 2003a). These approaches are discussed in greater detail in Chapter 5.

Stylized approaches are important in differentiating between scientific uncertainty, which is large and growing at all times, and uncertainty in the regulatory decision, which is manageable at all times. As discussed earlier in this chapter, these two concepts need to be kept clearly differentiated. The use of stylized approaches is an important tool in translating between the two. Hence, in situations in which scientific uncertainty is large and growing, it may be appropriate to use stylized approaches to manage those uncertainties. It is important that application of a stylized approach should encompass reasonable bounds on system behavior, so that the uncertainties are managed, not ignored.

3.2 Uncertainty Propagation in Current Performance Assessment Models

In this section, the observations of the TYMS panel presented in TYMS (1995) are considered in the context of a broader understanding of high-level waste disposal regulations and requirements. There are now several decades of experience in regulatory development for geological disposal facilities both nationally and internationally. This experience has demonstrated the importance of a number of considerations with respect to time frames in the regulatory process. These considerations are briefly reviewed in this section.

The regulatory process for deep geologic disposal of radioactive waste involves comparing projected future behavior of the repository system with some form of performance standards. This comparison is known in the US high-level waste program as Total System Performance Assessment (TSPA). TSPA analyses of Yucca Mountain have been independently conducted by DOE, NRC, and EPRI for nearly two decades. These analyses have primarily, but not exclusively, been focused on the first 10,000 years of the repository lifetime.

It has long been conventional to characterize uncertainties as one of three kinds: scenario (or future) uncertainty, model uncertainty, and parameter uncertainty (Kozak, 1994a; Kozak, 1997), even though there is often overlap and ambiguity in the characterization of a source of uncertainty into one of these categories. These uncertainties are propagated in current performance assessments in differing ways. Formal scenario development, screening, and justification methods have been developed over many years to manage uncertainties in the future state of the system. Model uncertainty approaches are somewhat less formal, but treatment of alternative conceptual models is a key part of the regulatory process, in which various stakeholders propose and attempt to support alternative conceptualizations of the repository system. Parameter uncertainties are most commonly addressed by assigning distribution functions to the uncertain parameters and propagating the uncertainty through the model to evaluate the corresponding uncertainty in the output variable. Growth in uncertainty in the performance assessment results is therefore the result of a growth in uncertainties in one of these uncertainty categories. It is useful to consider the implication of the TYMS (1995) recommendations in the context of each of these categories.

3.2.1 Growth in Scenario Uncertainties

The intent of scenarios is to provide a stylized way to address uncertainties about the future state of the system. For the most part, the scenario descriptions embody an understanding of the possible future evolution of the system, and to that extent the uncertainties in scenarios do not grow in time. A primary change in the TSPA related to scenario uncertainties is whether additional FEPs need to be accounted for at times in the distant future. In this way, alternative scenarios can be developed that incorporate the uncertainty about the future without the need to represent a growing uncertainty in time.

On the other hand, the particular scenarios that need to be included needs to be specified. In 40 CFR 197, EPA specified that only events with a probability of occurrence of 10^{-4} over 10,000 years (a nominal 10^{-8} annual probability) need to be considered in the TSPA for Yucca Mountain. Furthermore, EPA stated that events with probabilities greater than that value need not be considered if they lead to insignificant consequences. It might be argued that extending the time period of compliance to 10^{6} years would lead to a concomitant requirement to decrease the probability cutoff for scenarios accordingly. However, EPA has stated the basis for the probability cutoff to be based on the types of events that would be excluded from the analysis rather than the 10,000-year time period (66 FR 32100):

> Probabilities below this level are associated with events such as the appearance of new volcanoes outside of known areas of volcanic activity or a cataclysmic meteor impact in the area of the repository. We believe there is little or no benefit to public health or the environment from trying to regulate the effects of such very unlikely events.

The 10^{-8} annual probability therefore represents a clear exercise of EPA's statutory authority to establish levels of concern to protect the public, and is not primarily based on a 10,000-year time frame.

The TYMS panel recommended adopting the concept of "Negligible Incremental Risk" (NIR) to screen FEPs and scenarios associated with the potential for widespread contamination. They based this recommendation on the existing concept of "Negligible Incremental Dose" (NID) that has been recommended by radiation protection organizations (NCRP, 1993; ICRP, 2004). The concept is that scenarios and FEPs that have a sufficiently low combination of probability and consequence need not be considered in the compliance analysis. Instead of directly adopting this recommendation, EPA adopted an alternative FEPs screening concept based only on probability. If the scenario or FEP has a probability of occurrence less than approximately 10^{-8} per year, then it can be eliminated from further consideration. This is a very low screening level compared to the NIR/NID level suggested by the TYMS panel as a reasonable starting point for discussion.[6]

Thus, the current EPA screening limit is *very* conservative compared to the NID level suggested by TYMS (1995). It is likely that there are many FEPs that DOE has already included in their analysis using the EPA approach that would not have been included if the TYMS-recommended approach had been followed. Given that many additional FEPs are already included, it should be unnecessary to include any additional FEPs if the regulatory compliance period is extended

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[6] "We suggest the risk equivalent of the negligible incremental dose recommended by the NCRP [1 mrem/yr (NCRP, 1993)] as a reasonable starting point for developing consensus in a rulemaking process." (TYMS, 1995, pg. 60)

beyond 10,000 years. Given the increased uncertainties in the long time periods, even identifying FEPs with probabilities of occurrence as low as 10^{-8} per year will be difficult. If the NID concept were used, it is likely that no additional FEPs would be required to be included beyond those DOE has already included in their analyses for the first 10,000 years after repository closure. In fact, if the NID concept were applied for the first 10,000 years, it is likely that DOE would have had to address many less FEPs than they already have addressed. Maintaining the FEPs screening philosophy already used for the first 10,000 years is conservative in the sense of being overly inclusive, although it is unlikely to affect the mean dose estimates.

Application of the negligible incremental dose criterion in the context of Yucca Mountain could provide a secondary screening criterion. In 40 CFR 197, the 15 mrem/y dose limit for off-normal scenarios is applied as a probability-weighted dose. Applying similar logic, and applying the negligible incremental dose concept, it could be argued that scenarios that provided dose risks below 1 mrem/y (dose risk equals the consequences when weighted by their probability of occurrence) could also be screened from further consideration. Application of this concept may require adoption of the negligible incremental dose criterion in a formal manner by EPA. More importantly, however, this approach would require a consequence evaluation of scenarios to demonstrate that their consequence would fall below the negligible dose criterion.

3.2.2 Growth in Model Uncertainties

Conceptual model uncertainty refers to uncertainty in the appropriate representation of the underlying physics and chemistry of the system, uncertainty in boundary conditions, and uncertainty in the appropriate form of equations used in the solution of the performance assessment.

Uncertainties in models to be applied to various phenomena increase in certain parts of the analysis as time increases. This occurs because of evolution of components of the system with time. As an example, there is much greater certainty regarding the state of waste packages prior to 10,000 years than thereafter. Prior to 10,000 years, the waste packages are well accepted to be substantially intact, whereas once they begin to degrade at some significant time beyond 10,000 years, there is uncertainty about the nature and specific amount of degradation that will occur at any time. This uncertainty is addressed in the TSPA through the use of models and parameter distributions that overestimate the rate of degradation. However, there is the potential that such conservatisms may compound themselves when, for instance, a conservative estimation of corrosion is linked to a tunnel collapse analysis, which may then result in a more conservative damage estimate owing to the assumed degraded state of the waste package.

EPRI (2003) evaluated the effect of early failure of waste packages, drip shields, and cladding on the overall performance of the Yucca Mountain repository. The results are shown in Figure 3-3. This figure shows the “nominal” case in which the spent fuel cladding, waste package, and drip shield all function as anticipated. The other four curves show the impact on dose risk assuming the: cladding; drip shield; waste package; and both the drip shield and waste package completely fail to function. The result in these latter four cases is earlier and more rapid failure rates for the overall EBS. It is seen that the failure rate of the engineered barrier system components has a marked effect on both the timing and value of the peak dose resulting from the TSPA.

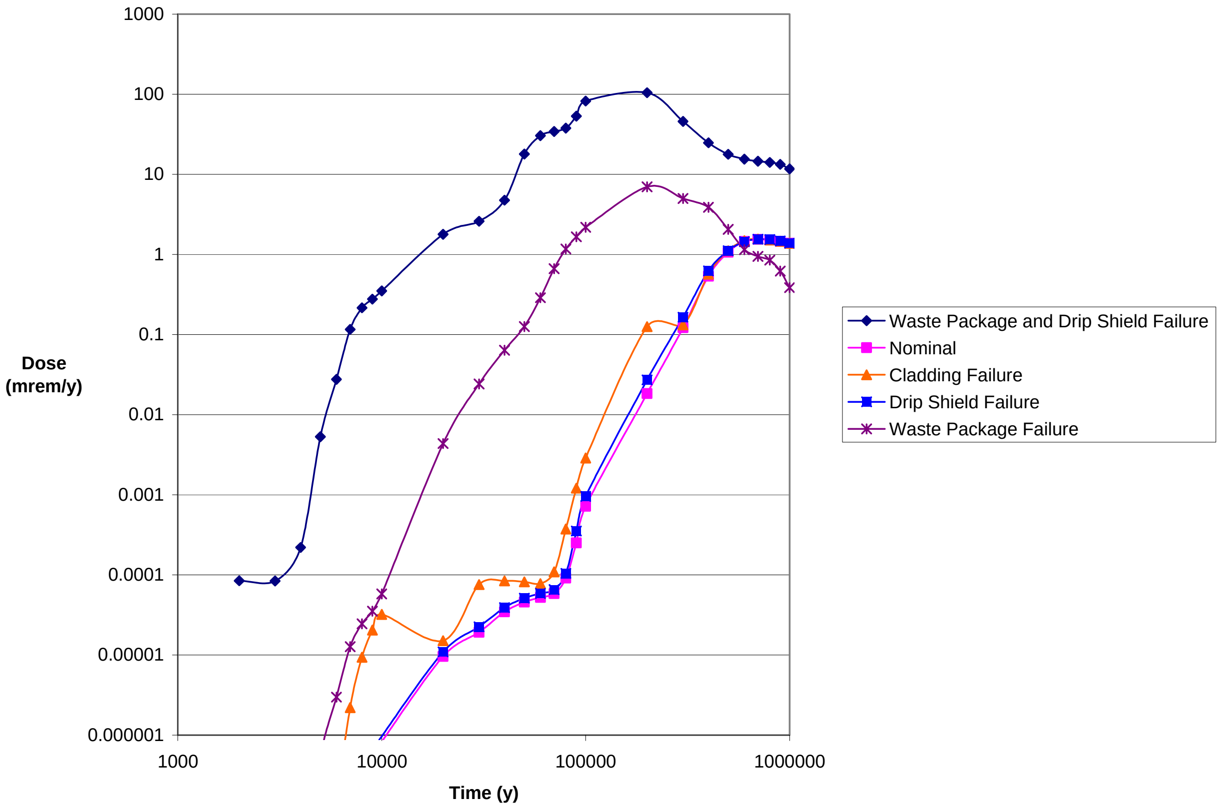

Figure 3-3
A comparison of mean doses resulting from rapid failure of cladding, waste packages, and/or drip shields, compared to the nominal results published by EPRI (2003).

These results demonstrate that differing analyses of the timing and rate of failure of components of the engineered barrier system can have a significant impact on the timing and value of the peak dose rate. It is also of note that the cumulative release from each of these curves at very long times is similar. Hence, the comments by TYMS (1995) that uncertainties in cumulative releases decreases with time is seen to be rigorously correct, but irrelevant to the peak dose performance measure.

A particularly important source of model uncertainty that arises at very long time periods is the influence of climate change, as it has the potential to affect a number of parts of the disposal system. The next chapter describes briefly the issues surrounding the incorporation of future climate change into total system performance compliance assessments for time periods exceeding 10^4 years, and a suggested way forward. Appendix A provides more detail on the subject of climate change.

3.2.3 Growth in Parameter Uncertainties

Parameter uncertainties are usually (though not universally) considered to be time invariant. That is, a probability density function is assigned to represent the uncertainty in the input parameter, and that probability density function applies to all times in the future. For such parameters, there can be an apparent change in the uncertainty of the output as a function of time. This occurs because of time lags in the disposal system, so that the influence of an uncertain parameter may not show up in the results for many thousands of years. As a consequence of this effect, the band of outputs from the TSPA may be different at two different times, as shown in the results from the TSPA-SR shown in Figure 3-4. This type of behavior has been misinterpreted to suggest that uncertainties remain constant or even decrease with increasing time, as discussed at the beginning of this chapter. However, the range of uncertainties shown in the figure only represents the evolution of a static uncertainty through the dynamic TSPA model.

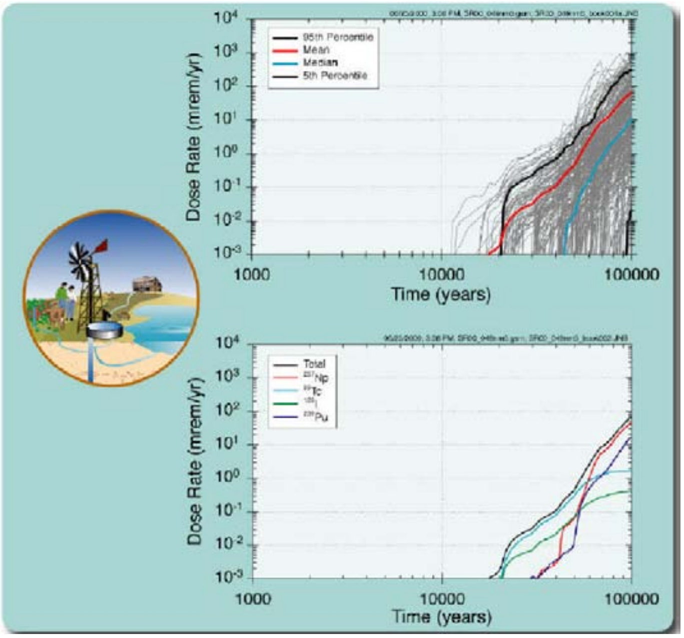

Figure 3-4
Results from the TSPA-SR showing an apparent change in the uncertainty in the results (DOE, 2000).

In other cases, an alternative probability density function may be applied at times in the future, to represent altered behavior under some assumed altered state of the system. So, for instance, a probability density function different than one appropriate at the present time might be applied to infiltration rate under an assumed altered climate state. This type of probability density function is qualitatively different, and contains an additional layer of uncertainty, than one developed for present day conditions. First, the parameters cannot be measured in the real system, even in principle, since the system is not observable under the conditions to which it applies. Second, the applicability of the parameter is linked to the likelihood of occurrence of the conditions it is intended to represent; that is, the parameter distribution contains implicit elements of scenario and model uncertainty. Consequently, it represents a growth in uncertainty in time that is embedded in the analysis.

This example shows that there is an additional element of uncertainty that enters parameter uncertainty at long times, when the system changes sufficiently that probability density functions appropriate for present day conditions no longer apply.

3.3 Summary of the Growth of Uncertainty

Uncertainties in a TSPA directed at projecting peak dose in the future grow significantly in the period after 10,000 years. These uncertainties arise mainly from uncertainties in boundary conditions, constitutive relationships, and parameter values needed to characterize a hypothesized future evolution of climate. The nature and degree of uncertainty in future climate states is similar to that associated with future human behavior: the general trends are known, but the details are too uncertain to permit elaboration. As a result, the range of uncertainty in the output of the TSPA represented by the variation of Monte Carlo realizations does not fully represent how uncertainty changes in time, and neither do they necessarily need to do so for the purposes of compliance assessment (Kozak, 1994). Rather, as discussed in this chapter, additional features of the uncertainty lead it to grow more quickly in time than is explicitly represented in the Monte Carlo realizations.

Furthermore, human behavior and climate are inextricably linked, as discussed in Chapter 4 and Appendix A; changes in one can lead to significant changes in the other. It becomes increasingly difficult to harmonize behavior of a RMEI with the environment in which the RMEI is assumed to exist: the analysis becomes internally inconsistent. Among the most difficult issues to deal with in the TSPA are the transient effects associated with the period of climate change. The existing projections by DOE for the post-10,000-year period illustrate the difficulties in characterizing the transient periods, as they produce spurious results that reflect model behavior rather than the behavior of the repository system. To a large extent, these uncertainties can be addressed in TSPAs by bounding the potential effects, rather than trying to incorporate them in detail in the TSPA.

These observations lead to the conclusion that a stylized approach is necessary to address climate change in the post-10,000-year period, and for the sake of internal consistency, to limit the FEPs that need to be considered in the post-10,000-year period. A series of potential approaches to that stylization are presented as options in Chapter 5, along with discussion of the strengths and weaknesses of each approach.

4

CLIMATE CHANGE

A particularly important source of model uncertainty discussed in Section 3.2.2 that arises at very long time periods is the influence of climate change, as it has the potential to affect a number of parts of the disposal system. This section describes briefly the issues surrounding the incorporation of future climate change into total system performance compliance assessments for time periods exceeding 10^4 years, and a suggested way forward. Appendix A provides additional detail on this subject.

4.1 Background

BSC (2004) notes the following about the impact of climate on hydrologic behavior of the Yucca Mountain system:

> "Climate controls the range of precipitation and temperature conditions at the land surface. The surface conditions (e.g., runoff, run-on, evapotranspiration) impact the rate of infiltration into the subsurface. Infiltration is defined as the flow of surface water downward across the atmosphere–soil or the atmosphere–bedrock interface. Net infiltration, which is the flow of water downward (i.e., drainage) below the root zone, controls deep percolation through the unsaturated zone. Percolation determines seepage that is important to the waste package performance, as well as groundwater recharge. Present-day and future infiltration is a key hydrologic parameter needed for design of the repository in the unsaturated zone at Yucca Mountain.

The amount of net infiltration deep into Yucca Mountain (recharge) has an effect on the total system performance. Higher net infiltration leads to the likelihood that a larger fraction of the repository disposal drifts could experience groundwater dripping from the tunnel roof and/or the drip rate in specific locations could increase. Furthermore, for solubility-limited radionuclides in the waste form, an increase in net infiltration could lead to a higher release rate from the waste form.

An important aspect of estimating the hydrologic response of the Yucca Mountain system is that detailed information about how rainfall is temporally distributed is required (EPRI, 1996; BSC, 2004). That is, it is not only important to be able to estimate whether a particular climate state results in warmer or cooler *average* temperatures, but whether rainfall is increased or decreased, by how much, and in which season. If, for example, a pluvial climate brought about increased rainfall in the winter months, when evapotranspiration was at a minimum, then the potential for increased net infiltration would exist. However, if the cooler average climate did not bring about increased rainfall, or it occurred in the summer months when evapotranspiration is higher, then there may be little effect on net infiltration. Furthermore, it is likely that net infiltration is dominated by relatively rare, heavy rainfall events. The alluvial fans existing in the Yucca

Mountain vicinity were caused not by the more "usual" rainfall events, but by these much rarer types of extreme events. There is considerable uncertainty about the details of these relatively rare events even for the present-day climate at Yucca Mountain. Detailed knowledge about the frequency and intensity of such rare rainfall events for past climates is essentially nonexistent.

Recently, the US Geological Survey (USGS) has developed an increasingly sophisticated basis for evaluating past variability in infiltration rate by examining the growth rates of calcite and opal in the Exploratory Studies Facility Tunnel (USGS, 2001; Paces et al., 2002; Marshall et al., 2003). These data suggest that the deep environment is buffered from dramatic changes in infiltration rates, even over time scales during which major pluvial events have occurred. DOE is taking increasing note of these data, and they may form part of the technical basis for estimating infiltration in the future (Andrews, 2005). At this stage, it is simply useful to note that there remains uncertainty in the linkage between climate and net infiltration at Yucca Mountain, and that past evaluations of the infiltration may have overstated the variability of infiltration in time. This is yet another example of the uncertainties associated with projecting system performance into periods in which pluvial conditions may exist.

For example, DOE notes the following regarding the ability to "predict" net infiltration responses to future climate states (BSC, 2004):

> Because long-term variations in climate occur, changes in net infiltration for future climates will occur as well. Predictions of spatio-temporal distribution of net infiltration for different climate states are likely to contain uncertainties associated with the selection of climate analog sites and corresponding records of precipitation and temperature…. The correlation analysis revealed that net infiltration is mostly dependent on precipitation, soil depth, bedrock permeability, and potential evapotranspiration…. *Because it is not possible to foresee every condition that could occur over the 10,000-year regulatory period, it is necessary to evaluate a range of possible scenarios to ensure that predictions of net infiltration are conservatively bounded within each of the climate scenarios predicted for the Yucca Mountain region.* (emphasis added)

This is consistent with the TYMS panel comments on climate change (TYMS, 1995):

> "In general, spatial boundary conditions of regional scale subsurface flow models are considered to be constant over time. There is at least one important exception to this generalization. The upper boundary to the geologic environment around the repository is the atmosphere. The average of atmospheric conditions is the climate, and it is well known that climate can vary significantly over geologic periods of time. Although the typical nature of past climate changes is well known, *it is obviously impossible to predict in detail either the nature or the timing of future climate change*. This fact adds to the uncertainty of the model predictions." (pp. 77-78) [emphasis added]

In addition to these uncertainties in the specifics of conditions during relatively stationary climatic conditions, uncertainties also exist as to the timing and rate of change of climate changes. NAS (2002) reviewed evidence of rapid climate changes in paleoclimate records, and concluded that:

> Large, abrupt climate changes have affected hemispheric to global regions repeatedly, as shown by numerous paleoclimate records … . Changes of up to 16°C and a factor of 2 in

> precipitation have occurred in some places in periods as short as decades to years … . However, before the 1990s, the dominant view of past climate change emphasized the slow, gradual swings of the ice ages tied to features of the earth's orbit over tens of millennia or the 100-million-year changes occurring with continental drift. But unequivocal geologic evidence pieced together over the last few decades shows that climate can change abruptly, and this has forced a reexamination of climate instability and feedback processes … . Just as occasional floods punctuate the peace of river towns and occasional earthquakes shake usually quiet regions near active faults, abrupt changes punctuate the sweep of climate history."

Furthermore, NAS (2002) emphasized the uncertainties in the constancy of climate states once these large-scale changes occur, and described additional rapid and unpredictable changes in climate on a smaller scale:

> "The quintessential abrupt climate change was the end of the Younger Dryas interval about 11,500 years ago, when hemispheric to global climate shifted dramatically, in many regions by about one-third to one-half the difference between ice-age and modern conditions, with much of the change occurring over a few years … . The changes affected many environmental parameters such as temperature and rainfall… . Weaker, but still of hemispheric extent, was a short cooling spell 8,200 years ago that lasted for about 200 years … . Although more regionally limited, the apparent change in El Niño behavior toward generally warmer and wetter conditions around 1976 … could also be considered an abrupt change."

Significant uncertainties can be introduced into the TSPA by consideration of these transient effects, and they have the potential to affect the way that climate influences peak dose calculations. Unless new evidence becomes available to better estimate historical net infiltration rates at Yucca Mountain, large uncertainties in future climate states may continue to have a significant impact on dose estimates beyond 10,000 years. Such a result partially jeopardizes the technical basis that the TYMS panel provided for its recommendation on the time period of compliance.

4.2 Surface Environment and Future Human Behavior

The surface environment is considered to refer to the geological and hydrological conditions of the first few tens of meters below the ground surface (IAEA, 1994a). This is the region that is most dramatically affected by changes in surface morphology (e.g. erosion and landsliding), human activities, and climate change. In this section, attention will be focused on the characteristics of the climate on the surface environment.

The surface environment will be significantly impacted by climate. In the Yucca Mountain region, the surface environment is expected to evolve to wetter conditions that may cause the formation of lakes and rivers of significantly higher flow rate than at present. Such changes would clearly lead to differences in water use and crops grown by humans living in the area at that time [IAEA, 2003]. Consequently, the uncertainties in future human behavior are the result of both intrinsic uncertainties in human behavior and in the near-surface environment that they would inhabit.

These observations show that in the post-10,000 year period, the near-surface environment at Amargosa Valley is expected to be dramatically different than it is at the present time. In this environment, assumptions made in developing the RMEI and groundwater concentrations become increasingly tenuous. The paleoclimate under some pluvial conditions correlates with the cooler climates in the states of Minnesota and Washington (EPRI, 1998), and their associated plant species. Under these conditions, with higher rainfall and cooler temperatures, the potential exists for agricultural practices near Yucca Mountain to follow those in the northern states as well. Even a rudimentary evaluation of the differences between conditions in Minnesota and those in Amargosa Valley shows that assumptions applied to pluvial conditions in Amargosa Valley would necessarily be speculative.

The details of the climate, the surface, and the near-surface environment are, therefore, unpredictable in a similar way and to a similar extent as human behavior. Both are predictable in their general characteristics but unpredictable in their specific details. Over the past few thousand years, the surface environment in Forty-Mile Wash has transitioned between perennial ponds and marshes to today's rare episodic flows, with conditions in between. Furthermore, there is a significant link between the details of climate change and the details of human response to the change.

One major aspect of human habit uncertainty is related to human action differences under differing climates. For example, present-day behavior in the Yucca Mountain region is largely governed by the generally hot, arid climate state that exists today. Use of groundwater and even the types of crops that can be grown are largely governed by the climate state. Agricultural practices and other human habits will *necessarily* change if Yucca Mountain undergoes significant future climate changes (BIOMOVS, 1996; BIOCLIM, 2003). That is, it would not be reasonable to assume the same behavior that is exhibited in the Yucca Mountain region today would represent behavior for a much cooler, wetter climate in the future at Yucca Mountain. The difficulty is, therefore, to specify not only present-day behavior for the present-day climate, but also future human behavior for each major future climate state without being almost entirely arbitrary in the selection of these future human behaviors. This argument suggests that there is a strong basis for establishing near-surface conditions by rulemaking rather than to include it as part of the TSPA modeling.

4.3 Potential Impacts on Total System Performance Assessment

Transitions between climate states are also numerically difficult to handle in analyses of subsurface flow and radionuclide transport. The difficulty in evaluation of transient flow conditions over long time frames may lead to issues derived from numerical compromises intended to bound the behavior of the system. One such issue was demonstrated in the Final Environmental Impact Statement (FEIS) for Yucca Mountain (OCRWM, 2002), where DOE published an analysis of doses in the post-10,000 year period that showed the effects of climate change on doses. DOE's FEIS carried out an analysis that assumed instantaneous changes between climate states (OCRWM, 2002); in this analysis the entire flow field was assumed to instantaneously change between one climate state and another. Furthermore, DOE assumed that the climate change occurred at the same time for all realizations, enormously magnifying the effect of these instantaneous changes at the assumed time of the climate change. The effect of these modeling assumptions is shown in Figure 4-1.

This modeling approach is inappropriate in that it is excessively conservative compared to an analysis that treats climate transitions as a change in boundary conditions to the flow analysis rather than as an instantaneous change between two states. Furthermore, given the uncertainty in the time of occurrence of the change in climate, the timing and rate of change of climate states should be assigned probability density functions, which would make the change in average dose associated with climate change at any one time insignificant. However, the simplified approach used in the FEIS was put forth for a specific purpose, a bounding estimate of potential environmental impacts, and hence, regulatory compliance did not rest on the results. The spikes shown in Figure 4-1 are therefore viewed as an artifact of the modeling approach used by DOE, rather than being indicative of repository performance. While this analysis served its intended purpose with respect to the FEIS, it is, in fact, highly misleading and should not be viewed as an indication of anticipated repository performance. Any use of these results in a regulatory compliance analysis would be inappropriate.

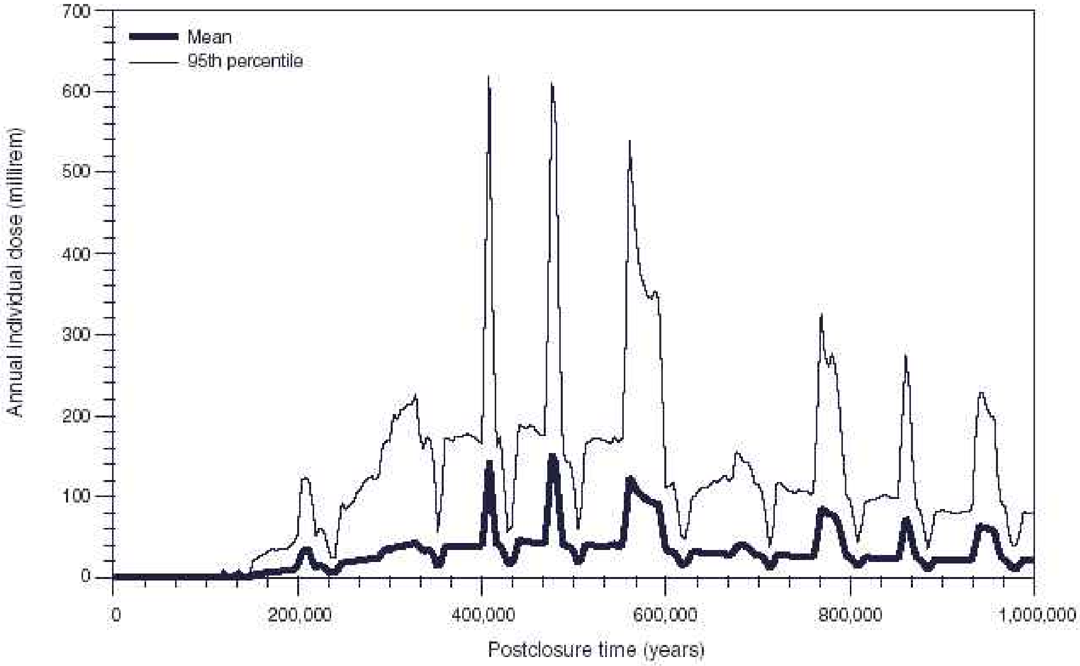

Figure 4-1
Post-10,000 year doses from the FEIS. The spikes are associated with modeling artifacts caused by assuming instantaneous climate changes and related hydrologic processes (excerpted from OCRWM, 2002).

The problem with attempting to deal with changes in climate state by using instantaneous transitions is that it does not make the performance assessment "meaningful" for the purposes of regulatory compliance. Should the peaks of the spikes in dose (or health risk) versus time curves become the basis for assessing compliance when such peaks are numerical modeling artifacts due to the lack of scientific knowledge about both the magnitude and rate of climate change? To do so would run counter to the expectations of TYMS (1995):

> "It should also be noted that the subsurface location of the repository would provide a temporal filter for climate change effects on hydrologic processes. The time required for unsaturated-zone flux changes to propagate down to the repository and then to the water

> table is probably in the range of hundreds to thousands of years. The time required for saturated flow-system responses is probably even longer. *For this reason, climate changes on the time scale of hundreds of years would probably have little if any effect on repository performance, and the effects of climate changes on the deep hydrogeology can be assessed over much longer time scales."* (pg. 92, emphasis added)

Unfortunately, a more internally consistent modeling approach, in which the climate, near-surface environment, and RMEI behavior are in correspondence at all points in the time domain, would appear to be very complex. This is because it would require the use of a variable RMEI, and sufficient knowledge of the details of future climate states and the transient behavior of the entire unsaturated and saturated zone.

To be internally consistent during a future climate state, the assumed future human behavior would need to at least be physically consistent with the boundary conditions imparted by that climate state. The TYMS panel notes the following about critical group definition: "…we agree that unrealistic assumptions [about human behavior] are inappropriate." (TYMS 1995, pg. 103) As discussed earlier and in Appendix A, in a significantly cooler and wetter future climate at Yucca Mountain, it will not be possible to grow some of the crops currently grown in the Amargosa Valley area. Perhaps most important, rainfall and/or surface water will supplant groundwater for at least part of the irrigation needs thereby reducing groundwater uptake.

Other details of the biosphere model would also need to change in response to a cooler, wetter climate. For example, dust resuspension will be lower due to higher soil moisture levels. Crops that can be grown in this new environment will have a shorter growing season than that existing in the Yucca Mountain region today.

Accommodating these changes due to a cooler, wetter climate while remaining internally consistent would require a change in assumed future human behavior from the present assumption of on-going present-day behavior in the Yucca Mountain vicinity. While there is some guidance how to select an analogue community in another region of the world that has behavior physically consistent with a future climate state (see, for example, IAEA, 2003), it would also require rulemaking to do so. It may be problematic to defend the specific choice in rulemaking since there may be many analogue agricultural communities in the world that have human behavior consistent with a cooler, wetter climate. Each would likely result in somewhat to significantly different biosphere dose conversion factors (BDCFs) if applied in a revised biosphere model (TYMS, 1995; IAEA, 2003).

The TYMS Committee noted the following about human behavior as it might be affected by climate change:

> "The third type of change that might result from climate change is a shift in the distribution and activities of human populations. In the vicinity of Yucca Mountain, a wetter, cooler climate would provide a more hospitable environment and could result in population increases. This could change the composition of the critical group by exposing more people to potential risks from the repository. However, even at the present time, the available ground-water supply could sustain a substantially larger population than that presently in the area. *Thus, there is no simple relation between future climatic conditions and future population."* (TYMS 1995, pg. 92, emphasis added)

Initial biosphere calculations carried out by EPRI[7] for alternative RMEI behavior under a postulated full glacial maximum are lower than present-day conditions by a factor of 2 or more, depending on the assumed conditions at the geosphere-biosphere interface. This decrease in biosphere dose conversion factors (BDCFs) is corroborated by independent analyses carried out for NRC (CNWRA, 2004, Table 3-11), and DOE (Rautenstrauch et al., 2003, Table 6-1) that show a general decrease in BDCFs during a pluvial period. Given the sensitivity to net infiltration in the DOE models, it is clear that large uncertainties in understanding the "details" of future general climate states at Yucca Mountain *may* result in large uncertainties in the performance assessment results, as indicated by Figure 4-1.

4.4 Additional TYMS Committee Comments on Climate

The TYMS Committee suggested that the climate states were reasonably boundable such that it would be possible to meaningfully model the effect on net infiltration:

> "Based on this [paleoclimate] record, it seems plausible that the climate will fluctuate between glacial and interglacial states during the period suggested for the performance assessment calculations [up to one million years]. Thus, the specified upper boundary, or the physical top boundary of the modeled system, should be able to reflect these variations (especially in terms of groundwater recharge)." (TYMS 1995, pg. 78)

However, the TYMS Committee made a number of different statements about the effect on climate change in the overall performance of the repository. On one hand, the Committee did not expect models including climate change to dramatically affect health risk or dose estimates:

> "Furthermore, even changes in climate at the surface would probably have little effect on repository performance deep underground." (TYMS 1995, pg. 71)

> "…a deep geologic repository is relatively shielded from the large changes in surface conditions…" (TYMS 1995, pg. 91)

This was an argument the TYMS Committee made to support their recommendation that uncertainties in climate would not prevent meaningful compliance assessments being made over time periods considerably longer than 10,000 years.

On the other hand, the TYMS Committee states that they *do* expect there to be an effect on the hydrologic response of the Yucca Mountain system:

> "Change to a cooler, wetter climate at Yucca Mountain would likely result in greater fluxes of water through the unsaturated zone, which could affect rates of radionuclide release from waste-forms and transport to the water table. [A] doubling of the effective wetness, defined as the ratio of precipitation to potential evapotranspiration, might cause a significant increase in recharge. An increase in recharge could raise the water table, increasing saturated zone fluxes." (TYMS 1995, pg. 91)

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[7] These analyses are not yet fully completed, and have not yet been published.

If the TYMS Committee had been convinced that climate shifts did cause a significant effect on the overall risk assessment, like that shown in the Yucca Mountain FEIS (Figure 4-1), they may have reached a different conclusion about the appropriate time period.

TYMS (1995) makes the following *general* comment about how to treat the uncertainties in climate change in performance assessments using some sort of “bounding” approach:

> “We conclude that the probabilities and consequences of modifications generated by climate change, seismic activity, and volcanic eruptions at Yucca Mountain are sufficiently boundable so that these factors can be included in performance assessments that extend over periods on the order of about 10^6 years.” (pg. 91)

Thus, TYMS (1995) clearly stated that, while it is known that the future climate state at Yucca Mountain will change, the details of such change are difficult to predict. In this sense, the issue of the unpredictability of the details of future climate states is similar to the unpredictability of the details of future human behavior. For example, there are aspects of human “behavior” that are reasonably boundable, such as human physiology, including the nature of radionuclide uptake into the body. It is the “details” of human behavior that are not easy to bound. Both, however, lack predictability of the details of their behavior well before 10^6 years. The lack of predictability of these details is a key consideration in developing a coherent standard that would apply to time periods much longer than 10,000 years.

While TYMS made it clear that a rulemaking approach to establishing human behavior within the context of the regulatory standard is required, TYMS was less clear how climate was to be dealt with. TYMS notes that climate states are “boundable” even for very long time frames, but provided no guidance on how to deal with important system features that are “boundable” other than rulemaking.

It is generally known that uncertainty of the future climate state will increase as time passes 10,000 years.[8] For a compliance period limited to 10,000 years, the magnitude of climate change is likely to be relatively limited such that there is less need to use rulemaking to deal with this issue. However, if a compliance time period considerably longer than 10^4 years is to be required, then an approach more like the one the TYMS Committee recommended for specifying future human behavior would also have to be applied to future climate. Thus, consistent with the recommendations by TYMS to use rulemaking in setting human behavior that is unpredictable, a substantial case can be made that rulemaking should also be applied to establish climate behavior. Aspects of climate change that could be established in rulemaking would include characteristics of one or more discrete climate states (e.g., seasonal/diurnal temperatures and precipitation in the Yucca Mountain vicinity) and the time(s) at which the discrete climate state(s) exist in the future.

4.5 A Way Forward on Climate

A possible approach to defining the long-term climate to be used to determine regulatory compliance in TSPA is to specify, in rulemaking, some of the necessary climate details such that an implementable performance assessment can be developed. This is consistent with the

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[8] See Appendix A for a brief survey of paleoclimate information relevant to Yucca Mountain.

approach recommended by the TYMS Committee for those FEPs whose details are not known. For the present-day interglacial climate, there would be a better technical basis for such specification in rulemaking. For other climate states, it would be necessary to somewhat more arbitrarily specify the details of those states, including the characteristics of the RMEI living in a different climate.

For example, DOE (BSC, 2004) has indicated that only three climate states need be used to reasonably represent general climates in the next 10,000 years:

> "[Climate] uncertainties are adequately addressed by the three climate states ["interglacial", "monsoon", and "glacial transition"], the estimated duration of future climate states (based on the precession methodology) compares favorably with that of past climate states (based on the fossil and isotope records), and that this forecast presents the best possible scientific assessment for future climates. Because there is no simple or objective way of assessing the nature of future climate uncertainties, only future observations could be used to validate the climate forecasting." (BSC, 2004)

It could be that only one additional climate state beyond the three identified by DOE, a "full glacial maximum," would be adequate to broadly define all reasonably anticipated climate states even well beyond 10^4 years. However, as discussed in Chapter 6, establishing the present day climate and human behavior in the Yucca Mountain region as the basis for future estimates is a reasonably bounding approach with respect to peak dose risk estimates.

The recommendation to fix the climate state in the compliance model to the present-day interglacial is based on the following considerations:

- Recent evidence suggest that net infiltration over time periods spanning multiple climate states has been more constant than previously understood;
- Biosphere dose conversion factors (converting, for example, groundwater concentrations into dose to the RMEI) for the present-day interglacial climate are reasonably bounding due to thigh groundwater use and higher atmospheric dust loadings;
- The goal of maintaining an internally-consistent compliance assessment requires that future human behavior be consistent with changes in the surface environment in different climate states. It would be impossible to avoid having to make largely arbitrary assumptions about such future human behavior since it doesn't exist in the Yucca Mountain region today; and
- The *only* climate state for which more detailed information is available upon which to develop and defend net infiltration and biosphere models is the present-day climate.

5

INTERNATIONAL APPROACHES TO ADDRESSING UNCERTAINTIES OVER VERY LONG TIMES

TYMS (1995) discussed the need to accept the use of bounding and stylized approaches for various aspects of the performance assessment. Yet the guidance provided in TYMS (1995) on how to implement bounding and stylized approaches in a very long-term compliance assessment is minimal. Furthermore, at the time TYMS (1995) was published, TYMS noted: "There is little guidance on potential exposures in the far distant future." (TYMS, 1995, pg. 41). Hence, it is necessary to supplement (not supplant) TYMS (1995) guidance.

Recognition of the increase in uncertainty at very long times is not unique to the United States, and perspectives developed in the international community support the use of such stylized analyses. Performance assessments related to repository projects are being conducted by many nations, and positions have been taken by international organizations with respect to time scales and treatment of the increase in uncertainty for performance assessment analyses. These positions are reviewed in this chapter.

5.1 ICRP Perspectives

Throughout the TYMS (1995) report, especially in the Executive Summary, emphasis is placed on basing a regulatory standard on the guidance and precepts of the International Commission on Radiological Protection (ICRP). For example, TYMS (1995) notes:

> "Additionally, EPA should rely on the guidance of ICRP that the critical group be defined using present-day knowledge with cautious, but reasonable, assumptions." (pg. 10)

It is therefore clear that TYMS (1995) recognized the importance of taking account of ICRP concepts in development of the standard. The ICRP reference in TYMS (1995) is ICRP 60 (ICRP, 1991), which was the most current ICRP guidance at the time of the TYMS report. More recently, ICRP (2000) has issued ICRP Publication 81 with new and revised opinions focusing on the safety assessment of geologic repositories. Much of ICRP 81 is devoted to considerations of time scales and the application of the ICRP system of radiation protection over those time scales, including the concept of the critical group.

ICRP (2000) notes that more information may be obtained for decision-making purposes from consideration of the probability (or likelihood) of occurrence of a particular situation giving rise to a dose separately from consideration of the resulting dose. This "disaggregated" approach would be based on a representative set of scenarios with various qualitative likelihoods (ICRP, 2000). The latter are not precisely quantified probabilities, but joint consideration of resultant dose with likelihood for specific scenarios would provide an evaluation of the radiological consequences of each scenario, balanced against the estimated magnitude of its likelihood. The decision maker would also need to take account of other factors in evaluating scenarios, such as duration and extent of doses. This approach is very similar to the one already embodied in 40 CFR 197 and 10 CFR 63, in which scenarios are considered in a disaggregated manner, balanced by their likelihood. To this extent, therefore, the existing rule and ICRP guidance are consistent.

ICRP 81 recognizes the use of alternative, complementary indicators in addition to dose/risk calculations:

> "To provide additional insight it may be useful to make qualitative comparisons particularly for the distant future, e.g. of the remaining hazard potential of a disposal system with the risks imposed by other natural or human-induced sources."

Nevertheless, ICRP 81 recommends the use of individual dose or risk calculations as the primary endpoint for the assessment. ICRP recognizes that the normal radiation protection framework does not apply directly to conditions in the far future, and notes that in TSPA:

> "…doses or risks are calculated under *reasonable selected test conditions* as if they were doses or risks as defined in the Commission's framework." (italics added)

That is, the ICRP 81 framework clearly recognizes that a critical group defined for purposes of radiation protection can only be applied under selected conditions.

In consideration of compliance estimates at future times, ICRP 81 states:

> "…one approach is the consideration of quantitative estimates of dose or risk on the order of 1000 to 10,000 years. This approach focuses on that period when the calculation of doses most directly relates to health detriment and *also recognises the possibility that over longer time frames the risks associated with cataclysmic geologic changes such as glaciation and tectonic movements may obscure risks associated with the waste disposal system.* Another approach is the consideration of quantitative calculations further into the future making increasing use of stylised approaches and considering the time periods when judging the calculated results." (emphasis added)

This idea of the use of stylized approaches and calculations is an important one, and forms the technical basis for the EPA's treatment of inadvertent human intrusion in 40 CFR 197 (EPA, 2001a). This concept is addressed later in this report.

In addition, ICRP 81 introduced, for the first time in the ICRP framework, the concept of the potential for multiple criteria with a different value associated with times far in the future:

> "…as the time frame increases, some allowance should be made for assessed dose or risk exceeding the dose or risk constraint. *This must not be misinterpreted as a reduction in the protection of future generations and, hence, a contradiction with the principle of equity of protection, but rather as an adequate consideration of the uncertainties associated with the calculated results."* (emphasis added)

It is unclear from this passage whether ICRP is saying that the constraint itself can be loosened, or simply if the acceptance criterion for a practice may change, such that doses greater than the constraint may be acceptable. This latter interpretation is equivalent to a relaxation of the level of conservatism of the analysis, allowing less conservative analyses to be compared to a dose constraint to reflect the "adequate consideration of the uncertainties." *Practically speaking, these two interpretations of the passage have the same impact on TSPA results: the dose constraint need not be applied as a strict limit in the distant future.*

Finally, ICRP 81 clearly indicates that doses in the far future should not be considered rigorous dose estimates to future generations:

> "Therefore, protection of future generations should be achieved by applying these dose or risk criteria to the estimated future doses or risks in appropriately defined critical groups. These estimates should not be regarded as measures of health detriment beyond times of around several hundreds of years into the future. In the case of these longer time periods, they represent indicators of the protection afforded by the disposal system."

This statement is consistent with the concepts in TYMS (1995) and in other international sources that doses in the future are not "predicted" in performance assessment but are regarded as stylized indicators of performance.

ICRP (2005) presents the ICRP's current recommended maximum values of dose constraints, which are reproduced in Table 5-1. In essence, four values are recommended according to the type of situation to be controlled. These values may be considered as giving the upper restriction that is to be applied by the appropriate national authorities to determine the most applicable constraints for the situation under consideration. The Commission expects that the resulting national values of constraints normally will be lower than the maximum value recommended by the Commission, but probably not by as much as a factor of ten. The dose constraints are established on a policy basis, from dose apportionment of a portion of the dose from all sources to any single anthropogenic source.

The maximum effective dose of 1 mSv/year (100 mrem/y) is recommended to select constraints in situations where there is a societal benefit, but no direct benefit for the exposed individuals. It also applies in situations where there is no environmental surveillance or monitoring or assessment and where individuals do not receive information or training. This value is also consistent with the scale of action: it represents a marginal increase of the natural background (a fraction of natural background). The 15 mrem/y dose limit in 40 CFR 197 and 10 CFR 63 is therefore seen to be conservative compared to international recommendations.

The value of an effective dose of 0.01 mSv/year (1 mrem/y) is the minimum constraint that should be considered for application in any situation. This value corresponds to a low need for action, giving rise to trivial risk to the exposed individuals. It is worth noting that this level is identical to the Negligible Incremental Dose recommended by NCRP (1993), which formed the basis for the recommendations by TYMS (1995) on Negligible Incremental Risk.

Table 5-1
Maximum dose constraints recommended for workers and members of the public from single dominant sources for all types of exposure situations that can be controlled (ICRP, 2005).

Maximum constraint (effective dose, mSv in a year)	Situation to which it applies
100	In emergency situations, for workers, other than for saving life or preventing serious injury or preventing catastrophic circumstances, and for public evacuation and relocation; and for high levels of controllable existing exposures. There is neither individual nor societal benefit from levels of individual exposure above this constraint.
20	For situations where there is direct or indirect benefit for exposed individuals, who receive information and training, and monitoring or assessment. It applies into occupational exposure, for countermeasures such as sheltering, iodine prophylaxis in accidents, and for controllable existing exposures such as radon, and for comforters and carers to patients undergoing therapy with radionuclides.
1	For situations having societal benefit, but without individual direct benefit, and there is no information, no training, and no individual assessment for the exposed individuals in normal situations.
0.01	Minimum value of any constraint

5.2 IAEA and NEA Perspectives

The International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) generally adhere to the recommendations of ICRP on radiation protection issues. However, they have also issued informal publications and have held workshops to investigate the issues associated with long-term time scales in performance assessment.

NEA (2002) distinguished between *time scales* of concern, and *time frames* for the assessment, and noted that different indicators of performance may be appropriate over different time frames. NEA (2002) represents the findings of individual contributors to a workshop intended to elaborate this concept. The primary break points discussed by workshop participants were the first 1000 years (the thermal period) and the first 10,000 years (prior to major climatic change).

IAEA has not established a single approach to a safety standard for geologic disposal, and significant debate continues within the waste management community of IAEA Member States. IAEA recognizes that a decision on acceptability should be based on reasonable assurance rather than absolute demonstration of compliance, and will permit latitude in the information to be considered when reaching a decision.

IAEA and NEA have been instrumental in the development and acceptance of the "Reference Biosphere" approach (e.g. BIOMOVS, 1996; BIOMASS, 1999; IAEA, 2003; NEA, 2004). NEA (2004) describes this concept as:

> "Assumptions regarding the characteristics of the surface environment and the nature of future human society and actions must nevertheless be made if dose and risk are to be evaluated and tested against regulatory and design targets. There is international consensus that a "stylised approach" is an appropriate means to define these assumptions. … The approach involves defining a range of alternative "credible illustrations" or "stylised situations," including, for example, different possible future climate states, agricultural practices and exposure pathways, and analyzing the resultant dose or risk for hypothetical critical groups. This avoids open-ended speculation on issues such as future human habits for which uncertainties are large and irreducible."

Comparable concepts were used by TYMS (1995) in their recommendations, and EPA used this type of approach in developing its Reasonably Maximally Exposed Individual (RMEI) approach in 40 CFR 197. The approach in 40 CFR 197 is therefore consistent with current approaches recommended by IAEA and NEA.

5.3 European Commission Perspectives

The SPIN Project (EC, 2002) notes that dose criteria are useful at all times, but emphasis should be placed on them only at early times when human and biosphere conditions can be specified reliably. Specific time frames for which these criteria apply were not discussed by EC (2002).

The BIOCLIM (2003) program examined the use of biosphere modeling in the context of long-term performance assessments. Texier et al. (2003) discussed the use of time-varying "reference biospheres" (BIOMOVS, 1996) to develop an internally consistent performance assessment depiction of the disposal system at any point in time in the future. This extension of the BIOMOVS (1996) and BIOMASS (1999) methodologies to account for climate evolution illustrates the interdependency of the biosphere with other parts of the TSPA. Indeed, the use of a time-invariant biosphere was discussed in BIOCLIM (2003) primarily in the context of a TSPA with time-invariant climate. It is clear from the discussion in BIOCLIM (2003) that a primary consideration motivating the study was the desire for internal consistency in the TSPA as the system evolves into the future.

5.4 Timescales as Implemented in National Waste Disposal Regulations

Regulations governing deep geologic disposal of HLW/spent fuel for several nations are summarized in Table 5-2. While there are differences in details arising from regulatory, political and social perspectives among nations, 10,000 years into the future is broadly recognized as representing a point in time when something in the analysis should change. For a number of countries, this change is represented by a shift away from direct dose or risk analyses after 10,000 years. However, most countries continue to pose the regulatory goal in the post-10,000-

year period as some form of dose or risk. After 10,000 years, the growth of uncertainties associated with climate, the near-surface environment, and human behavior are viewed as rendering dose or risk calculations as increasingly less reliable.

NRPB (1992), the UK regulatory authority, states that

> "For times up to about 100 years after the closure of the site, it may be assumed that some form of institutional control will remain. During this period, the system of dose limitation should be applied. For times greater than 100 years or so, but less than about 10,000 years into the future, the Board considers that the risk to members of the critical group should be estimated for comparison with the risk constraint. As the time period of an assessment increases, assumptions about the human environment and human behaviour will necessarily become increasingly arbitrary, and therefore should be replaced by more general ones. *Gradual changes in such assumptions may be difficult to implement in assessments, and therefore, for simplicity, the Board recommends that general assumptions should be applied after about 10,000 years.* The Board considers that individuals who might be alive beyond about 10,000 years will be adequately protected if calculations indicate that suitably chosen, hypothetical reference communities would not be exposed to unacceptable risks." (emphasis added)

That is, after 10,000 years the analysis changes from a direct dose analysis to one in which the biosphere is treated based on hypothetical reference assumptions. It is notable that the NRPB recognizes the difficulties with addressing gradual changes, which is among the current concerns in the post-10,000 year period for Yucca Mountain. NRPB addresses these gradual changes by recommending the use of stylized approaches to eliminate the arbitrariness of the consequent analysis.

SKI and SSI, the Swedish regulators, are currently changing their positions, and the eventual form of their updated thinking is not yet clear. However, it can be seen in Table 5-2 that, to date, 1000 years is viewed as the longest time over which individual dose assessments are to be carried out. In their most recent guidance in draft form, SSI (2004) has issued a draft for comment on proposed general guidelines on the application of regulations for protection of humans and the environment from spent fuel and nuclear waste. As part of that proposed guidance, the issue of time frames of assessment is addressed. SSI (2004) subdivides the postclosure period into three segments:

- For periods in the first 1000 years, the assessment should be done accounting for considerable detail, paying particular attention to *"… conditions and processes in the early development of the repository, which can affect its long term protective capability …,"* and *"… biosphere conditions and other known trends in the environment …"* characterizing the *"present-day biosphere."*
- For periods after 1000 years out to 10^6 years, the analysis should *"be successively regarded as an illustration of the protective capability of the repository assuming certain conditions."* SSI further notes that "for very long periods, hundreds of thousands of years, the risk analysis may be based on a stylized description of future cycles of major climatic changes, and large harmful occurrences such as earthquakes. The intention should be to shed light on the protective capability of the repository and to provide a qualitative picture of the risks."
- For periods past 10^6 years, no account need be given.

SSI (2004) recommends that, within these constraints, the assessment should be carried out until the occurrence of the peak consequences, or 10^6 years, whichever comes first. It is recommended that the assessment be carried out "for at least 100,000 years or the period of a glacial cycle, to shed light on reasonably foreseen strains on the repository."

Several other countries (e.g. Canada, Switzerland) have not published significant positions on time frames.

Table 5-2
Timescales used in national regulations (from McCombie and Chapman, 2002).

Timescales in national waste disposal regulations	
Canada	Time frame for quantitative compliance 10,000 years; requirement that longer periods be addressed qualitatively to ensure that no sudden increase in risk would occur
Finland	Up to 'reasonably predictable time periods' (~10,000 years), dose constraint from expected evolution; beyond, quantities of nuclides migrating to be below specified limits (derived from natural backgrounds)
France	Stability of geological barrier to be demonstrated for a period of at least 10,000 years; calculations of dose for normal evolution extend to 100,000 years; thereafter the situation is 'hypothetical'
Germany	No timeframe officially specified; recommendation of the RSK for dose calculations to 10,000 years and use of other safety indicators thereafter
Sweden	Little formal guidance on timescales; SKI and SSI preparing new regulations which uses individual dose to 1000 years and collective dose thereafter
Switzerland	Doses and risks shall 'at no time' exceed specified values
UK	The official guidelines specify a risk target for the post closure period which is of undefined duration. The advisory body, NRPB, has proposed different approaches for different time periods (NRPB, 1992)
USA	40 CFR 191 (EPA, 1993) specifies dose limits for 1000 years, cumulative release limits for 10,000 years, groundwater permissible concentrations for 1000 years; 10 CFR 60 (NRC, 83a) specifies 'substantially complete containment' for 300-1000 years, water travel times of at least 1000 years; 40 CFR 197 (EPA, 1999) requires compliance demonstration for 10,000 years, presentation of results to peak dose or risk

Note on Table 5-2: the time period of compliance for groundwater permissible concentrations in 40 CFR 191 is misstated in McCombie and Chapman (2002). The actual time period of compliance for groundwater concentrations is also 10,000 years.

Among countries examined by McCombie and Chapman (2002), only Finland uses performance indicators other than dose in the period greater than 10,000 years. In addition, only Finland stipulates these performance indicators in law in a manner similar to the US approach to regulation (NEA, 2004). Consequently, it is worth elaborating on the Finnish concepts in more detail.

5.5 Finland: Distinct Periods for Alternative Safety Indicators

In this section, a brief review is presented of the structure of the Finnish high-level waste regulation. As discussed above, the Finnish example is interesting because (a) it uses different performance indicators in different time frames, and (b) it specifies them in law, unlike many other European countries. At the outset, it is necessary to acknowledge that the specific features of the regulation cannot be directly transferred to Yucca Mountain. The near-surface environment, biosphere, and human actions in Finland are anticipated to be totally disrupted during a full glacial maximum. This situation contrasts with the situation at Yucca Mountain, which is characterized by a cooler climate than current, increased rainfall, and the formation of lakes. Nevertheless, the logic of the Finnish regulation is useful to examine as the basis for an approach to deal with uncertainties in the far future.

Finnish regulations (STUK, 2001; Ruokola, 2002) differentiate four time periods in which different criteria are defined. These periods are

1. The operational period, which extends to the end of an assumed post-closure monitoring period. During this period appropriate dose limits are applied.
2. The environmentally predictable future, which extends to 10,000 years. Appropriate dose constraints are applied during this period, with specified environmental exposure pathways to be considered.
3. The era of extreme climate changes, which extends from 10,000 years to about 200,000 years into the future. During this period, the Finnish regulations specify radionuclide-specific release limits.
4. The farthest future (beyond approximately 200,000 years). At this stage, no specific quantitative compliance calculations are required.

The fundamental basis and justification for these divisions is the influence of climate on the biosphere and near-surface geosphere. It is clear in the Finnish situation that the onset of glaciation results in profound and irreversible changes in near-surface conditions at the site, while the deep geological conditions remain stable. Therefore, while this is different than the situation at Yucca Mountain, the underlying message is that as the uncertainties in the near-surface conditions grow in time, the Finnish regulations explicitly call for addressing those changes through explicit regulatory conditions that stylize the performance assessment.

6

MATCHING REGULATIONS TO TIME SCALE AND TIME-DEPENDENT FACTORS

A number of potential options exist regarding how to implement regulations in the post-10,000-year period. In this section, a brief review is presented of some of those considered most viable, along with issues associated with each. A regulation involving compliance periods in excess of 10,000 years must include provisions that:

- Are consistent with the Court ruling;
- Result in a “meaningful” standard that protects public health and safety in a constructive and equitable manner; and
- Are “reasonable” and would be implementable in a regulatory environment.

Here, "implementable" means that NRC would be able to determine that appropriate information and analyses were presented upon which NRC could make a compliance determination for such a long compliance period. A “meaningful” regulation should require that the conceptual models in the compliance assessment be internally consistent, in which all parts of the analysis are significant to real potential consequences that may arise from the repository, and which lend themselves to clear understanding of the implications of the analysis to the regulatory decision. This argues for practical, clear boundaries to be established in the regulation to avoid undue speculation about unusual conditions that are not central to the performance of the facility.

The imposition of consistent, meaningful, and implementable conditions in the regulation calls for the definition of a set of stylized conditions to be specified in the regulation. As discussed in Chapter 3, a stylized approach is defined as:

> A set of assumptions established by policy that is used to limit the range of uncertainties considered in the performance assessment, while retaining its ability to protect public health and safety.

In this report, arguments have been established that show that stylization is necessary to address climate change and determine the FEPs that need to be considered in the TSPA. Such stylizations are necessary to ensure that the TSPA does not become based on an arbitrary set of conditions, in which the most scientifically uncertain components of the system drive the results. Stylizations need to be established to retain the elements of the analysis that pertain to public safety, while eliminating those parts that lead to undue technical uncertainties based on arbitrariness. Only by stylizing the analysis can the regulation be made implementable.

6.1 Option 1: Carry Out Analyses to Peak Dose Using Present-day RMEI

In this approach, the TSPA would be carried out to peak dose using multiple climates with abrupt climate state transitions, and the present-day RMEI assumptions, regardless of the inconsistencies between those assumptions and the climatic state. There are two problems with this option. The first is the lack of internal consistency between assumptions in the climate and in the near-surface environment and RMEI behavior. The second is that assuming abrupt climate state transitions can cause abrupt changes in individual risk or individual dose estimates.

Regarding the first problem, it could be postulated that the entire near-surface environment is treated in a stylized manner from time zero, but such a position becomes weaker if the projected near-surface environment is dramatically different than present day. Such an approach might also be interpreted to be inconsistent with the statement in TYMS (1995):

> "Selection of a time scale for the standard must therefore take into account the scientific basis for the performance assessment itself." (pg. 30)

As has been discussed in this report, the scientific basis for TSPA involves more than just the scientific basis for geological stability. Treating present day near-surface conditions as fixed and stylized while allowing climate changes creates a deliberately self-inconsistent conceptual model of the system. Such an approach would also be inconsistent with the TYMS quote given above.

In summary, simple extension of the current 40 CFR 197 standard to the post-10,000 year period leads to an internally inconsistent analysis that renders the performance assessment less meaningful, which is contrary to the recommendations of TYMS.

6.2 Option 2: Post-10,000 Years with a Fixed RMEI and Limited Climate Change

As time increases, the link between a fixed RMEI behavior and future climate becomes increasingly tenuous. For instance, extrapolation of the TSPA beyond 10,000 years requires that the fixed RMEI behavior is assumed to apply during the glacial maximum climate state – a climate state that would likely change dramatically the need to use groundwater, the type of crops grown, and other aspects of the local environment that will affect potential exposure pathways.

To obviate the difficulties of this approach, it could be postulated that dose projections need to account for climate change during the first 10,000 years, but that stylized projections into the post-10,000 year period only need to project the same degree of climate variability that is used in the first 10,000 year period. In this way, internal consistency is maintained between the RMEI and the climate needed to maintain it, unreasonable combinations of climate conditions are not included in the analysis, and the dose peaks due to modeling artifacts, such as those indicated in the FEIS (Figure 4-1), should be largely avoided.

The idea of performing stylized analyses past 10,000 years is supported in the literature (IAEA, 1994; NEA, 2002; Smith et al., 2003), and in national legislation (Table 5-2). This approach meets the criteria of both the Court and EPA. It addresses the NAS recommendation to carry out the analysis to peak dose, and eliminates the disconnection between the RMEI and climate. In addition, the number of scenarios for future system states to be considered in the long term is reduced to those few with potentially significant impact on system performance. This is consistent with TYMS statements about some aspects of the system only being "boundable," and is consistent with the need for a standard that can be implemented in NRC's regulatory framework.

The potential objection to this option is that it is highly likely there will be significant climate change in the Yucca Mountain area beyond 10,000 years. To exclude consideration of alternative climate states may, potentially, not be acceptable. Furthermore, it can be implied that the intent of TYMS, with the words about future climates being "boundable," was that the regulation requires consideration of a range of climate states.

6.3 Option 3: Post-10,000 Years with a Time-dependent RMEI

Another way to maintain consistency between the RMEI and the climate state is to allow for a time-dependent definition of the RMEI. This approach would be similar to the use of a time-varying "reference biosphere" approach (BIOMOVS, 1996), recently under investigation in Europe (BIOCLIM, 2003; Texier et al., 2003). There is precedent for this approach in the literature, as this is the way time dependence is evaluated for Drigg (UK) and Dounreay (UK) facilities, since they are coastal sites and climate, in the form of sea level change, could affect them greatly. Similarly, elements of this approach appear in the Finnish regulations, discussed in Section 5. However, in the framework of the US regulatory structure, this approach would require regulatory definition of the behavior of the RMEI, through rulemaking, at future climate states.

Establishing this approach would necessitate defining specific RMEI assumptions in the rule for different climatic conditions. These assumptions would necessarily be speculative, since climatic conditions and near-surface environmental conditions are similarly speculative. Use of analogues to other sites with current climates similar to the potential future climate at Yucca Mountain has its own difficulties. The selection of the analogue can lead to different results, depending on the characteristics of the site chosen. This difficulty is probably not insurmountable, as the establishment of an analogue would proceed by policy direction rather than by technical arguments. Since biosphere dose conversion factors during a pluvial period are below those for the interglacial period, doses during the full glacial maximum, in which infiltration is presumed to be at its maximum, are offset to some extent by likely features of human water usage and hydrological dilution. *Results from the current interglacial are therefore likely to bound the potential doses associated with other climate states when differences in human behavior between climate states are taken into account.*

Modeling results have been shown to be sensitive to the details of climate state transitions (magnitude and rate of transition, and details of annual rainfall and temperature distribution). Given that the details for future climates at Yucca Mountain are largely speculative, it would be best to specify these details in rulemaking. Thus, a more serious difficulty with this approach is that the timing, duration and magnitude of the timing of changes between climate states would need to be specified for the duration of the analysis.

To implement this option, the following would have to be established *in a rulemaking proceeding*. First, the climate states to be considered would have to be established. Second, the state of the near-surface environment in response to the stylized climates would have to be established. Since those responses may be time-dependent, it would also be necessary to establish the time of occurrence of the changes to each new climate state, and the time period over which the transition occurs. Only at that point could a speculative RMEI be defined for each stage of the climate state in the TSPA. In other words, a stylized temporal sequence of climate changes, the response of the natural system to that sequence, and the response of people to the changes in the natural system would all have to be established via rulemaking and codified in the regulations. Considerable emphasis would have to be placed on the highly uncertain transient behavior in the transitions between climate states, to ensure that modeling artifacts, or other largely arbitrary climate assumptions, do not dominate the compliance assessment. It is not reasonable to base compliance of the repository on the specious transient behavior between climate states.

It is not clear whether the use of this option would be more or less “bounding” compared to other possible approaches, particularly as the doses will depend on the specific features of the RMEI chosen to represent future human behavior. Increased rainfall in the future may lead to higher releases from the repository, but may also lead to increases in the dilution to which radionuclides would be subjected. Water use patterns would change, and the basis for how these would be incorporated into a regulation is uncertain. As suggested earlier, BDCFs for a pluvial climate would likely be lower. Therefore, there is doubt whether a pluvial climate would cause increases in dose compared to simply assuming the current interglacial climate for all time. It may be simpler, yet no less bounding to avoid the need to specify the details of future climates, and the RMEI behavior that would be consistent with these future climates altogether.

6.4 Option 4: Multiple Steady State Analyses

This option is intended to address the potential objections to Options 2 and 3. The former is viewed as potentially objectionable for not considering the full range of climates in the post-10,000-year period, while the latter is unduly focused on the transient parts of the future evolution of climate. To remedy these issues, calculation of a range of steady-state climate situations that span the range of variability of potential future climates anticipated for Yucca Mountain could be required. That is, one TSPA analysis would reflect the current-day climate, current-day near-surface environment, and current-day RMEI, as in Option 2. However, alternative climate states would be required to be evaluated, assuming that they apply in a steady-state manner from today. So, for instance, one analysis might assume full glacial maximum rainfall, the presence of surface lakes expected in those conditions, and a RMEI based on a comparable climate analogue. As discussed in Option 3, the current interglacial conditions likely provide an upper bound on future doses. Similarly, a full glacial maximum, with higher rates of dilution and lower biosphere dose conversion factors, likely provides a lower bound on potential doses.

The primary disadvantage of this option is that multiple compliance assessments would have to be generated. Each would have to be presented and defended. While this is not unprecedented, it will add to regulatory complexity.

6.5 Option 5: Dose Analysis for 10,000 Years with an Alternative Performance Measure Thereafter

In this approach, the dose assessment would be carried out to 10,000 years as it has in past TSPAs, after which it would be replaced by a comparison with natural fluxes or natural doses, in a manner similar to the Finnish example cited in Chapter 5. The technical approaches supporting this approach have not yet been developed, and there remain technical challenges to developing a coherent standard to this approach. It is unclear whether a revised standard would be more or less restrictive than any of the other options. Selection of this option would therefore introduce significant uncertainties in the regulatory process. Furthermore, this option was viewed with distinct disfavor by TYMS (1995), which stated that "*without calculations of dose or risk, a release standard appears arbitrary*," and "*it does not produce information that is easy to understand or to compare with other risks* (pg. 64)."

6.6 Option 6: Alternative Post-10,000-year Dose Limits

In this approach, the 15 mrem/y standard would be replaced by a different standard after 10,000 years. One argument for this approach is that since the RMEI is inconsistent with water-use patterns in the post-10,000 year period, a different dose standard could be used to rectify this difference. A second argument would be that the use of dose apportionment at long times is tantamount to projecting assumptions about future human behavior. Any selected apportionment would represent a fundamental assumption about the number of radiation sources to which an individual might be exposed, and any such assumption is clearly speculative. In the long term, therefore, the use of a dose constraint intended to represent dose apportionment is necessarily arbitrary.

A potential argument against this approach might be that it violates the principle of intergenerational equity. However, ICRP 81 stated clearly that

> "…as the time frame increases, some allowance should be made for assessed dose or risk exceeding the dose or risk constraint. This must not be misinterpreted as a reduction in the protection of future generations and, hence, a contradiction with the principle of equity of protection, but rather as an adequate consideration of the uncertainties associated with the calculated results."

Therefore, there are technical and ethical arguments to support this option.

A second approach to this option would be to consider less stringent radiation protection standards that might apply in the far distant future. The logical basis for this argument would be that today's radiation protection standards reflect an implicit evaluation that they are reasonably achievable. As already demonstrated in Chapter 5, other international organizations, notably ICRP and IAEA, recommend higher individual dose limits than that imposed by EPA. A 100 mrem/y limit represents, to a large extent, a judgment that it is both achievable and protective when applied to the public. Moreover, in other circumstances, precedent exists to permit higher acceptable doses to account for pragmatic considerations. So, for instance, radiation workers in the DOE are permitted 5,000 mrem/y; the current occupational limits recommended by the ICRP and the FAA for flight crews is 2,000 mrem/y; and ICRP 82 presents a graduated scale of doses in excess of 100 mrem/y for mitigation of contaminated lands based on practicality of cleanup. The point of identifying these higher limits is twofold:

- They are intended to address a practical constraint about implementation, and
- They are considered protective, within that constraint.

A sensible argument about an acceptable long-term dose might involve establishing a dose for which there is no observable effect, in the absence of the conservatism often invoked in normal situations of radiation protection. An acceptable approach might be to establish an upper limit dose limit as a function of the variability of background dose in the US. As NCRP (1987a) notes, such variability is understood only qualitatively, but they go on to note that almost all of the variability is the result of inhalation associated with radon. The subsequent qualitative discussion by NCRP (1987a) suggests that the variability to natural background exposures is on the order of ± one order of magnitude. Hughes and Riordan (1993) suggested that the range of exposures to natural background in the UK is 100-10,000 mrem/y about an average of 220 mrem/y. Ghiassi-nejad et al. (2002) report no statistically significant chromosomal consequences associated with very high background radiation levels in Iran (>10,000 mrem), and provide anecdotal evidence that there is no increase in cancer or decrease in life expectancy associated with these dose levels.

The average background dose in the United States is about 300 mrem/y (NCRP, 1987a); in Amargosa Valley background is about 400 mrem/yr (http://www.ocrwm.doe.gov/factsheets/doeymp0337.shtml). Thus, even if the concept of dose apportionment was used with an upper limit dose (from all man-made sources) that was equivalent to natural background in the Yucca Mountain vicinity, a dose limit from an individual man-made source of greater than 100 mrem/yr could be justified.

The significance of these observations is relevant to establishing protective standards applicable in the far future. Okrent (1999) has discussed the intertwined issues of intergenerational vs. intragenerational equity. Briefly stated, just as the current generation should not impose undue burdens on future generations, so the current generation should not suffer undue burdens to mitigate negligible risks in the far distant future. The predominant weight of evidence suggests that doses up to thousands or even tens of thousands of millirems are associated with negligible risk, and are within the range of variation of natural background doses. It is therefore reasonable to ask whether doses on the order of or in excess of background might be acceptable if applied to a hypothetical person living in the extreme future.

7

ELEMENTS OF A NEW YUCCA MOUNTAIN STANDARD

In this chapter, a set of elements are identified that would form a satisfactory basis for the standard from a technical perspective. These elements are based on several assumptions about requirements for the standard, all of which are "based upon and consistent with" the TYMS (1995) recommendations:

- It is assumed that the standard will be based on peak dose to an individual, based on the RMEI approach;
- It is assumed that the standard will require calculation of peak dose at whatever time it occurs out to a maximum of one million years; and
- It is assumed that the standard will provide adequate protection of the public.

As is discussed in this report, these requirements dictate that the peak dose will be calculated at a time in which the uncertainties associated with climate change and other significant factors are increasing, and at a time when consideration of human behavior is intractable. It is therefore necessary, from a technical perspective, to stylize and limit the boundaries of the analysis.

7.1 Considerations in Developing the Standard

7.1.1 The First 10,000 Years After Closure

As has been discussed earlier, the current set of standards addressing the first 10,000 years after repository closure are stringent, yet it appears that they are implementable. The RMEI dose limit of 15 mrem/yr is a factor of anywhere from two to an order of magnitude below recommendations by others. The FEPs screening criterion of 10^{-8} per year is very stringent compared to the Negligible Incremental Dose (NID) concept recommended by TYMS (1995). While uncertainties certainly grow significantly during the first 10,000 years after closure, it appears that DOE and NRC have, in a long series of pre-licensing discussions, come to agreement on the general approach to be taken in implementing the existing regulations during the first 10,000 years after repository closure.

Therefore, it makes sense to retain the existing regulations for the first 10,000 years after repository closure "as is." It is only necessary to consider a revised approach for time periods beyond 10,000 years.

7.1.2 Effects of Considering the Post-10,000 Year Period

NEA (2004) has described in clear terms the ethical and environmental basis for geological disposal. The use of multiple and redundant engineered and natural barriers leads to isolation of the waste for extremely long periods of time. Plans are enacted to protect public health and the environment at all times in the future, and the detriment associated with releases is seen to be acceptable, and is not considered to be a major liability passed to future generations (NEA, 2004). As a result of the long times of containment, it is inevitable that projections of performance become increasingly difficult and uncertain. As a result, application of stylized approaches to manage the growth in uncertainty has become necessary. Indeed, it is precisely because the disposal system is so effective that these difficulties arise.

Arguably, a new regulation promulgated as a result of the July 9, 2004 Court ruling need not result in greater protection of the public or environment during the regulatory period than would have been achieved by the previously existing regulations. Doses associated with the current design and performance assessment analyses that have been developed to address the 10,000-year standard have already been shown to be extremely small. For example, the current TSPA carried out by DOE shows that, for the nominal scenario, releases before 10,000 years are solely the result of potential manufacturing defects. This observation makes the clear case that the system of natural and engineered barriers at Yucca Mountain provides outstanding isolation of the waste.

Rather, the Court ruling may simply force a change in the method of compliance assessment. Performance assessments developed to date by DOE, which were not optimized for the post-10,000 year period, and which were not intended as compliance analyses, such as the analysis in the FEIS (Figure 4-1), may need to be reevaluated in light of the Court ruling. The difficulties in formulating an acceptable regulation for the post-10,000 year period arise because the Yucca Mountain repository system is so effective that it isolates wastes until the time in which the level of uncertainty becomes large. Extending the period of compliance beyond 10,000 years with increasing uncertainties may make it more difficult to demonstrate compliance with the regulation without necessarily improving disposal system safety.

7.1.3 Intergenerational and Intragenerational Equity

NAPA (1997) has established four basic principles to apply to problems in which intergenerational equity plays a role:

- Trustee Principle: Every generation has obligations as trustee to protect the interests of future generations.
- Sustainability Principle: No generation should deprive future generations of the opportunity for a quality of life comparable to its own.
- Chain of Obligation Principle: Each generation’s primary obligation is to provide for the needs of the living and succeeding generations. *Near-term concrete hazards have priority over long-term hypothetical hazards.* (emphasis added)

- Precautionary Principle: Actions that pose a realistic threat of irreversible harm or catastrophic consequences should not be pursued unless there is some compelling countervailing need to benefit either current or future generations.

Each of the options described in Chapter 6 adheres to these principles. In no case would any of the options lead to "irreversible harm or catastrophic consequences," and in all cases protection of the public is maintained. Consequently, the selection among the options may be limited to the pragmatic considerations associated with implementation of a regulatory standard over very long time periods.

7.1.4 Consistency between RMEI Behavior and the Climate State

Individual doses are at the core of radiological protection. However, TSPA calculations of doses after a period of several hundred years can only be regarded as guiding estimates. This view is shared by all national and international authorities that have commented on repository-related performance assessments. Regardless, EPA (66 FR 32099) expressed concern about their ability to specify reasonable bounds on RMEI behavior in the post-10,000 years:

> "One of the aspects of uncertainty relates to the impact of long-term natural changes in climate and its effect upon choosing an appropriate RMEI. For extremely long periods, major changes in the global climate, for example, a transition to a glacial climate, could occur … . We believe, however, that over the next 10,000 years, the biosphere in the Yucca Mountain area probably will remain, in general, similar to present-day conditions due to the rain-shadow effect of the Sierra Nevada Mountains, which lie to the west of Yucca Mountain … . As discussed by NAS, however, for the longer periods contemplated for the alternative of time to peak dose, the global climate regime is virtually certain to pass through several glacial-interglacial cycles, with the majority of time spent in the glacial state ([TYMS, 1995], p. 91). **These longer periods would require the specification of exposure scenarios that would not be based upon current knowledge or cautious, but reasonable, assumptions, but rather upon potentially arbitrary assumptions**." [emphasis added].

Embedded in the concept and definition of the reasonably maximally exposed individual (RMEI) of Part 197 is the knowledge that today's human behavior (e.g., partial use of locally-produced food using groundwater irrigation) is strongly influenced by today's climate (i.e., warm inter-glacial period). TYMS (1995) notes on page 92 that what "…might result from climate change is a shift in the distribution and activities of human populations."

Given the prevailing view that the present-day climate state will not drastically change in the next 10,000 years, it was relatively straightforward for EPA to fix the RMEI characteristics for a 10,000-year compliance period. Much beyond 10,000 years into the future, however, it is anticipated that the climate is likely to change dramatically. Furthermore, the *details* of the future climate state are uncertain, although TYMS states the belief that future climate states are "boundable."

Within the RMEI concept, human behavior (based on present day behavior) is *de facto* matched to a consistent climate (present day climate). While past climatological evidence supports a duration of the present inter-glacial climate for approximately the next 10,000 years, the same evidence indicates a change to a cooler, wetter glacial climate after 10,000 years. Areas in the region of Yucca Mountain, such as Death Valley, become large inland lakes, the vegetation becomes more forested, and, as noted by the TYMS, the human behavior associated with this changed environment will not resemble today's human behavior.

TYMS (1995) notes (pg. 77)

> "Although the typical nature of past climate changes is well known, it is obviously impossible to predict **in detail** either the nature or the timing of future climate change." [emphasis added]

Therefore, after 10,000 years, knowledge of the details of future climate states will diminish dramatically, and the explicitly assumed interrelationship of present day human behavior with present day climate in the RMEI definition becomes increasingly discrepant and inappropriate.

If the climate state changes significantly, it becomes internally inconsistent to continue to assume human behavior remains unchanged in a different climate state – something that TYMS implies should be avoided in a "meaningful" standard and assessment. Hence, an approach to "stylizing" uncertain future climate states and even more uncertain RMEI behavior must be developed using rulemaking to achieve a "meaningful" standard.

7.1.5 Determining What Scenarios are to be Included

In 40 CFR 197 and 10 CFR 63, provision is made to account for scenarios that have a reasonable chance of occurrence over 10,000 years. This provision is distinct from the 10,000-year compliance time frame, and as a result this provision of the regulation has not been remanded. This approach is clearly supported by TYMS (1995):

> "Specifying exposure scenarios therefore requires a policy decision that is appropriately made in a rulemaking process conducted by EPA…"

TYMS (1995) discussed the potential to use the concept of "negligible incremental risk" to define which scenarios and conditions should be included in TSPA. This concept is briefly discussed as follows. NCRP (1987, 1993) proposed establishing a public dose or risk level below which negligible consequences could be assumed. NCRP (1987) adopted a negligible risk level of 10^{-7} y^{-1}, and NCRP (1993) equated that risk level to an annual negligible dose of 1 mrem/y.[9] TYMS (1995) suggested that similar levels[10] could be adopted to define which scenarios and conditions should be included in a TSPA, and which could be excluded as minimally important. The concept explicitly used by TYMS (1995) was to demonstrate that an analysis showing acceptable risks to a critical group would provide negligible risks to a wider population group, for situations in which widespread exposure was possible.

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[9] NCRP adopted positions are not obligatory on Federal Agencies. The fact that NCRP has adopted these positions does not mean that they have been adopted as policy elsewhere in the Federal government, only that the levels are scientifically supported.

[10] TYMS suggested a negligible incremental risk level equivalent to 1 mrem/yr.

The TYMS panel recommended adopting the concept of “Negligible Incremental Risk” (NIR) to screen FEPs and scenarios associated with the potential for widespread contamination. They based this recommendation on the existing concept of “Negligible Incremental Dose” (NID) that has been recommended by radiation protection organizations. The concept is that scenarios and FEPs that have a sufficiently low combination of probability and consequence need not be considered in the compliance analysis. Instead of directly adopting this recommendation, EPA adopted an alternative FEPs screening concept based purely on probability. If the scenario or FEP has a probability of occurrence less than approximately 10^{-8} per year, then it can be eliminated from further consideration. This is a very low screening level compared to the NIR/NID level suggested by the TYMS panel as a reasonable starting point for discussion.

Thus, the current EPA screening limit is *very* conservative compared to the suggested NID level made by the TYMS panel. It is likely that there are many FEPs that DOE has already addressed that would not have been included had the TYMS-recommended approach been used. Given that many these additional FEPs have already been included, it seems unnecessary to include any additional FEPs for time periods beyond 10,000 years. Given the increased uncertainties in the long time periods, even identifying FEPs with probabilities of occurrence as low as 10^{-8} per year will be difficult. In any case, if additional FEPs screening for the time period beyond 10,000 years is required, such screening should be based on the NID concept for these long time frames. It is likely, however, that no additional FEPs will be required to be included beyond those DOE has already included in their analyses for the first 10,000 years after repository closure. In fact, if the concept of negligible incremental dose were applied for the first 10,000 years, it is likely that many less FEPs would be screened in. But maintaining the FEPs screening already used for the first 10,000 years is conservative in the sense of being overly inclusive, but unlikely to affect the mean dose estimates.

Application of the negligible incremental dose criterion in the context of Yucca Mountain could provide a secondary screening criterion. In 40 CFR 197, the 15 mrem/y dose limit for off-normal scenarios is applied as a probability-weighted dose. Applying similar logic, and applying the negligible incremental dose concept, it could be argued that scenarios that provided consequences below 1 mrem/y when weighted by their probability of occurrence could also be screened from further consideration. Application of this concept may require adoption of the negligible incremental dose in a formal manner by EPA. More importantly, this approach would require a consequence evaluation of scenarios to demonstrate that their consequence would fall below the negligible dose criterion.

However, evaluating consequences for a comparison to a NID criterion may be relatively straightforward. It may be possible to make simple bounding estimates whether the NID level would be exceeded. For example, if a different microbially-influence corrosion (MIC) mechanism beyond 10,000 years might occur, the use of bounding calculations could be done to estimate both the probability of that new mechanism occurring, and the consequence if it did occur. For example, if the probability of occurrence of the new MIC mechanism was determined to be no higher than 10%, and the NID level was 1 mrem/yr, then a bounding calculation could be developed to determine if the dose consequence due to the new MIC mechanism was greater than 10 mrem/yr (1 mrem/yr divided by 0.1 (10%)). If the dose consequence was lower than that level, then the new MIC mechanism would be screened out.

7.1.6 Application of a Graduated Dose Standard

Several arguments can be made to support the concept of a graduated dose standard, with a higher dose limit applicable to the period beyond 10,000 years. The first of these arguments is derived from the fundamental principles of radioactive waste management (IAEA, 1995). IAEA (1995) established nine fundamental principles to guide responsible management of radioactive waste. These principles form the basis for all radioactive waste management activities internationally, and form the fundamental basis for the Joint Convention on the Safety of Spent Fuel and Radioactive Waste Management. Principle 4 states that:

> *"Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today."*

This principle is customarily interpreted to mean that the accepted dose limit of 1 mSv/y (100 mrem/y) shall be the limit of exposure to all sources of man-made ionizing radiation. However, ICRP (2000) has noted that in certain circumstances, this approach may be modified as a result of practical considerations. In the case considered by ICRP (2000), costs and exposures associated with intervention result in higher permissible intervention levels. ICRP (2000) recommended that for doses on the order of 10 mSv/y, intervention may be necessary, but at doses on the order of 100 mSv/y, intervention is almost always justifiable. It is worth considering the implications of this recommendation. The ICRP has, with this recommendation, acknowledged that these higher dose limits are a justifiable modification of the normal dose limit, are applicable when practical considerations interfere with the normal system of radiation protection, and most importantly, ***these dose limits are still adequately protective of public health and safety***. This system recognizes, for the first time in ICRP recommendations, that application of dose limits and dose constraints at these low dose levels represents a value judgment about the balance between doses received by a member of the public and costs associated with offsetting those doses. It is a small incremental step from that position to considering the applicability of higher dose constraints at long times, and to offset the practical issue of managing the growth of uncertainties as a function of time.[11]

As discussed in Section 5.1, ICRP (2005) has recently expanded on this concept to develop a more self-consistent view of the maximum annual dose constraint applicable to different situations. ICRP (2005) notes that resulting national constraints are expected to be lower than the maximum values, but probably not be as much as a factor of ten. Evaluation of the principles set out in Table 5-1 suggests that annual doses on the order of 10 mSv (1000 mrem) may be acceptable if there is an offsetting benefit. However, it is even easier to make the case that annual doses up to 1 mSv (100 mrem) are fully protective of the public in uncontrolled circumstances.

A more broadly based argument for relaxing the dose standard at very long times is derived from arguments on the ethics of intergenerational and intragenerational equity. Applying a relaxed constraint at very long times is morally and ethically equivalent to discounting future doses, in the manner that future costs are discounted in economic analyses. Belzer (2000) has made arguments that such discounting is both appropriate and necessary to make sound decisions. He

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[11] It is noted that ICRP has not made this incremental step in their recommendations, but limit themselves to the more direct cost-benefit relationships in remedial action decisions involving imminent risk.

presents logical arguments to rebut many familiar positions opposing such discounting. Of particular importance is his observation that the Precautionary Principle, a major foundation of the ICRP radioactive waste management principles, is "…the expression of an extremely high aversion to certain risks and not to others…" Belzer's refutation of the Precautionary Principle notes that implicit in its application is the concern that decisions made today may lead to catastrophic consequences in the future. Belzer notes this argument is flawed for reasons both ethical and logical. However, in addition, for radioactive waste management, application of the Precautionary Principle leads to a consideration of not catastrophic future risks, but extremely small risks at very long times in the future.

These arguments are similar to those made by Okrent (1999). The National Academy of Public Administration (NAPA) developed similar arguments (NAPA, 1997), leading to policy choices by US Government agencies to manage other types of radioactive waste considering much shorter time periods. Under the current DOE Order O435.1, for instance, individual doses calculated in performance assessments need only be calculated and compared to performance objectives for the first 1000 years. Similarly, residual levels of contamination for sites undergoing decommissioning and decontamination are based on analyses that are truncated at 1000 years.

If these arguments are coupled (i.e., that discounting of future doses can be ethical) with a proposed moderate increase in the dose constraint at long times, there is the potential to derive significant benefit to the current generation while having negligible effect on far distant generations. Application of a moderate degree of discounting to the Yucca Mountain regulation would ensure that management of high-level waste would be conducted in a manner that ensures the health and safety of the public while being consistent with approaches used in managing other classes of waste in the United States.

7.2 Proposed Features of a New Yucca Mountain Standard

While it is recommended that the basic criteria within current 40 CFR 197 and 10 CFR 63 be retained for the first 10,000 years after repository closure, it is necessary from a purely technical perspective to limit the conditions that need to be analyzed to meet the requirements of a regulation extending to time periods beyond 10,000 years. All of the options identified in Chapter 6 have certain common elements, which are features that should be addressed in the development of the new Yucca Mountain standard:

- The regulation needs to recognize that, as a result of the increase in uncertainty after 10,000 years, there is a need to specify stylized conditions for the period after 10,000 years. The current 40 CFR 197 and 10 CFR 63 stylize human behavior, giving clear boundaries on the range of conditions that need to be incorporated into the analysis. In a new regulation with an extended regulatory time period, a comparable level of stylization is appropriate for establishing bounds on climate, and on FEPs that need to be considered in the analysis. These additional stylizations are necessary, since the uncertainties of climate and human behavior in the far future introduce an arbitrariness to the analysis while not increasing public protection.
- A reasonable approach to handling climate would be to specify steady-state climate conditions applied to the duration of the analysis. This would avoid the conceptual and

computational difficulties in evaluating system behavior during transients between climate states – especially when uncertainties in the “details” of those future transitions are large. Given that it is unclear whether consideration of a pluvial climate will even be bounding compared to simply assuming the present-day interglacial climate continues until the time of peak dose, it would be no less arbitrary to establish, by rulemaking, that the present-day climate state should be assumed for the entire compliance period. This latter approach is preferred as it avoids the need for DOE to make largely arbitrary assumptions about the details of how a future climate state would be expressed (in terms of net infiltration, human behavior, and other biosphere changes) at the Yucca Mountain site.

- The increases in uncertainty at long times as well as issues of balancing intergenerational and intragenerational equity argue for a relaxation of the current stringent 15 mrem/y dose constraint for the time period beyond 10,000 years. From a purely technical perspective, and in harmony with international recommendations on radiation protection, a dose constraint on the order of 100 mrem/y can be considered to be protective of public health and safety in uncontrolled circumstances.
- FEPs to be retained in the analysis should be based on the current standard of 10^{-4} probability *during the first* 10^4 *years*, with an allowance for omitting FEPs that are judged to have low consequence to the analysis. In essence, this approach supports the concept that the current FEP screening, based on the initial 10,000 year time period, is acceptable (and conservative) as the basis for the longer-term analysis. Alternative arguments are possible using the concept of Negligible Incremental Risk, which show that the 10^{-8} per year probability cutoff is extremely conservative compared to negligible dose and risk values. Given increased uncertainties in the long time periods, even identifying FEPs with probabilities of occurrence as low as 10^{-8} per year will be difficult.

  Therefore, it is recommended that the FEPs screening for the existing regulation (i.e., applicable to the first 10,000 years only) need not be revisited for time periods beyond 10,000 years due to the very inclusive nature of the FEPs probability cutoff used during the first 10,000-year period. If EPA or NRC choose to require additional FEPs screening for time periods beyond 10,000 years, then the screening criterion should be based upon the concept of Negligible Incremental Dose, per TYMS (1995).

The above recommendations have been developed to be “based upon and consistent with” the TYMS (1995) recommendations. Furthermore, the above recommendations are both “reasonable” and implementable, and provide for a high level of protection for future generations by balancing the burden between present and future generations.

8
SUMMARY OF RECOMMENDATIONS

The goal of this report has been to consider technical implications and options associated with regulatory compliance periods in excess of 10,000 years that:

- Are consistent with the Court ruling;
- Result in a "meaningful" standard that protects public health and safety in a constructive and equitable manner; and
- Would be "reasonable" and implementable in a regulatory environment.

To achieve these goals, it is recommended that the revision to 40 CFR 197 should incorporate the following key features:

- Revisions to the regulation should be carried out in a surgical manner, such that the existing regulations for Yucca Mountain remain unchanged for the first 10,000 years after repository closure.
- Analyses carried out for the post-10,000 year period should be conducted in a stylized manner. This stylized approach is intended to allow projection of repository performance in a manner that protects public health, but which does not introduce elements that require arbitrary scientific assumptions to carry out the analysis.
- To this end, it is recommended that climate behavior should be fixed at a steady state throughout the analysis, to avoid the technical difficulties in evaluating a transient and hypothetical set of future climate trajectories. The current interglacial climate provides a likely upper bound to the conditions for TSPA that may be found from alternative climate states.
- Human actions should be consistent with the postulated climate. It would therefore be consistent to use the current RMEI approach with the current interglacial climate, projected out to peak dose. Such an approach would be protective, as current conditions are likely to produce higher individual dose estimates than alternative assumptions.
- Features, Events, and Processes (FEPs) included under the current regulation reflect the use of a very conservative cutoff criterion. Including additional FEPs beyond those presently addressed in the TSPA would be overly conservative and unnecessary. It is therefore recommended that part of the stylization for the post-10,000-year analysis would be to exclude any additional FEPs not already considered in the pre-10,000-year period.
- Consideration should be given to applying an alternative, higher dose standard after 10,000 years. From a strictly technical perspective, doses on the order of 1 mSv/y (100 mrem/y) are considered protective under all potential exposure situations. Application of constraints below 100 mrem/y is tantamount to applying assumptions about future human behavior,

since it relates to assumptions about the need for dose apportionment. However, despite these technical considerations, application of a higher dose standard is primarily a policy decision.

The combination of an extremely long time frame for performance with a peak dose criterion could, therefore, ironically but logically drive DOE to the use of a less robust engineered barrier system, which would fail at times less than 10,000 years when the uncertainties in the state of the system are less than at later times. However, it is believed that DOE would not consider, yet alone adopt, such a position. The reason to raise this point is to recognize that the fact that the maximum doses do not arise until the far distant future is a representative characteristic of a good site and repository design. In carrying out analyses to peak dose, the regulatory structure should be established in a way that recognizes this fact, and which does not make compliance assessments for a good site and design more onerous than for a less robust system.

EPRI seeks feedback from all parties on the issues and recommendations made in this report.

9

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A
CLIMATE CHANGE AND EVOLUTION

In this appendix, competing scientific views on climate change are reviewed. Several topics are covered in detail: the past record of glacial/interglacial climate cycles and their use as analogue models for future climate change; numerical climate model predictions for modern, past, and future climate; the relationship between climate changes and hydrological responses of the Yucca Mountain System; and other potential analogues for future climate change based on a ‘greenhouse climate’ trajectory derived from an early Eocene paleoclimate analogue. It is emphasized that the consequences of these alternative views are significantly different, and would likely have a significant effect on human activities and near-surface phenomena in the Yucca Mountain region. They will likely have a lesser effect on the deep geological and hydrological conditions at Yucca Mountain.

The appendix focuses on whether there is sufficient knowledge to be able to describe future climate at Yucca Mountain “in detail” such that it is possible to model future climate as it affects other features, events, and processes (FEPs) important to estimating individual doses. This includes uncertainties in the paleoclimate record, both world-wide and in the Yucca Mountain vicinity, and uncertainties in the local hydrologic response to wetter paleoclimates. Changes in modes of climate variability and the consequences of arbitrary assumptions about the future evolution of the mean climate state are highlighted.

A.1 Background

Yucca Mountain will experience a climate significantly different than the present day climate over the next million years. There is currently significant scientific debate over the trajectory that future climate will take over that period, and there is no current consensus in the scientific community. Among the most important issues in the debate is whether current levels of CO_2 in the atmosphere represent a triggering mechanism, which may disrupt the climate trends of the past several million years. A portion of the community of climate change scientists suggest that natural conditions may be overridden during the next few centuries by an anthropogenic greenhouse effect. In this view, in the post-greenhouse era, natural geological processes will again control climate, and the glacial/interglacial cycle will resume. A different portion of the climate change scientific community has proposed a substantially different trajectory for future climate evolution, based on the warm, greenhouse climates of Earth’s past. Advocates of this theory suggest that the Earth may be in a period of major transition to a future significantly warmer than today, including a loss of polar ice. Such conditions would be similar to conditions prevailing some 55 Mya. Future climate in this case may see an end to the glacial-interglacial cycles that have typified the last several million years. By contrast, other scientists believe that the future climate trajectory is not primarily controlled by atmospheric CO_2, but by other mechanisms. In this case, future climate can be expected to be closer to climate in the geologically recent past, and the trend toward repeated cycles of interglacial conditions and pluvials would be expected to continue. If natural conditions prevail, controlling factors associated with past climate changes suggest that the future will present a variety of conditions ranging from somewhat warmer to significantly cooler climates.

This scientific debate bears directly on the ability to establish a new Yucca Mountain standard based on sound science. Selection of any particular trajectory for future climate would be somewhat arbitrary, because the range of potential future conditions associated with differing scientific opinion is large. Clearly, any details of global climate change used in the analysis would be somewhat arbitrary, including rate of change and even the end states to which it is trending. Furthermore, the relationship of these global trends to the site-specific conditions at Yucca Mountain is uncertain. Globally wetter conditions have the potential to lead to drier conditions in the Yucca Mountain region.

These scientific uncertainties argue for a stylized approach to treating climate in the post-10,000 year period at Yucca Mountain. This argument is strengthened when one considers that the climate will have an impact on future human behavior, which is already treated in a stylized manner in regulation, and that future human behavior may have an impact on climate in the sense of possible anthropogenic warming. The linkage between human behavior and climate change is therefore seen to be both significant and uncertain.

A.2 General Paleoclimate History

A.2.1 General Overview of Paleoenvironmental Proxies

Data about climatic change and the interaction between components of the Earth system and life can be gleaned from the geologic record. For example, in certain time periods, even tens or hundreds of millions of years ago, seasonal variations in temperature and rainfall can be assessed. In other cases changes in the ocean circulation and carbon cycle can be assessed that occurred on time scales as short as 1,000 years. These data are founded on the use of climate proxies, stand-ins or indicators of past climatic properties or processes. Some candidates for use as proxies include physical properties and chemical and isotopic compositions of minerals, fluids, or gases found in the ocean, on land, or in glacial ice. Other possibilities include aspects of the anatomical or assemblage structure of certain fossil plants and animals, or even merely their presence or absence in the fossil record of a locality.

On land, climatic variables that have been the traditional focus of proxy investigation include the mean annual, maximum and minimum, and seasonal distribution of temperature, precipitation and net evaporation. In the ocean, the key variables include currents, temperature, salinity, nutrient availability, productivity, and redox chemistry. Biodiversity patterns, continental weathering rates, winds and storminess have also been the target of proxy analysis.

Considerable effort in reconstructing paleoenvironmental history from proxies has been carried out in the past decade. Older, low resolution records, with weak temporal constraints and poor spatial coverage are being supplemented and replaced by higher resolution records with better age control and spatial coverage. New proxies have been developed and some established proxies have seen new applications. New proxies and independent lines of proxy evidence have allowed scientists to extract new information about the climate system. Proxies can be quantitative, yielding estimates of climatic parameters to which essentially precise (but not necessarily accurate) numbers can be put. This is accomplished via *transfer functions*, using regressions or other statistical methods to calibrate relationships between properties measurable in the geologic record against climate parameters observable today.

Both qualitative and quantitative proxies require the assumption that the calibration relationship that holds true in the present held true in the past. In the best cases, this relationship is bolstered by agreement between the modern calibration and some theory derived from first principles or a strong biological or physical constraint. No climate proxy is truly sensitive to only one climatic parameter, so the most robust characterizations of paleoclimates are established when multiple proxies (preferably both quantitative and qualitative) are present for the same climate characteristic. When multiple proxies are applied it is possible to play the weakness of one proxy against the strengths of another and constrain a larger number of climatic parameters by doing so.

For several decades, the most heavily studied proxy for reconstructing climates in the distant past has been the oxygen isotopic composition ($\delta^{18}O$) of calcium carbonate, denoted here as δ_c. Importantly, δ_c depends on a number of factors. First is the isotopic composition of the sea water in which it grows (δ_w), the latter being a function of changes in global ice volume on land and regional changes in the surface net evaporative balance. As a consequence of this dependence, δ_c has long been used as a indicator of terrestrial ice-volume changes. Second, the fractionation between δ_w and δ_c by the foraminifera is temperature dependent, with a relationship that is generally predictable. Challenges to unraveling a climate signal from oxygen isotopes in foraminiferal calcite such as this are significant, but they have been used as the basis for major evaluations of data. For example, Zachos et al (2001) have created a high resolution (~20 kyr interval) deep-sea δ_c compilation shown in Figure A-1. When combined with other proxies and environmental information, these data suggest (1) the general cooling of the deep ocean from 12°C to slightly below 0° over the past 65 million years, (2) the orbitally-modulated oscillations overlying that trend, and (3) the rapid transitions that punctuate this trend as brief and sudden warming occurred at the beginning of the Eocene, and as ice sheets were emplaced in the Antarctic at the end of the Eocene.

A.2.2 A History of the Cenozoic

Studies of paleoclimates suggest that over the past 100 million years, Earth's climate has evolved in a significant and complex way. Change has occurred on all time scales, from gradual trends of warming and cooling with time scales of 10^5 to 10^7 years, orbitally-paced rhythmic climate cycles with periods of 10^4-10^6 years, and climate shifts that initiate on time scales of 10^0-10^3 years, such as the little Ice Age of the 17th century.

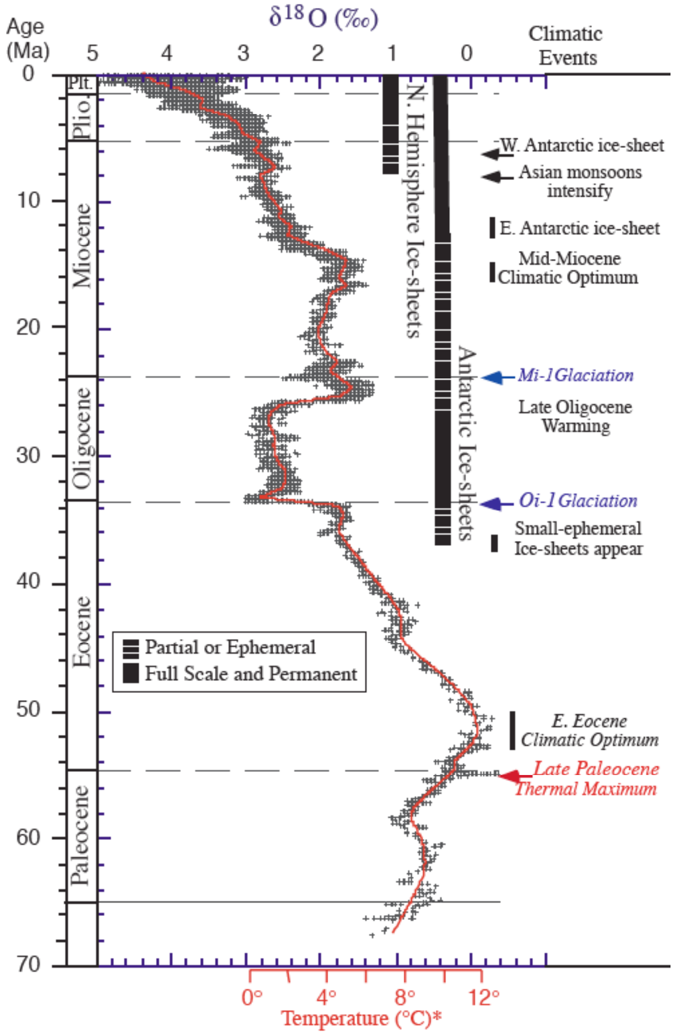

Figure A-1
δ^{18}O changes over the last 70 Myr. From Zachos et al. (2001).

For most of the past 100 million years, Earth's mean climate state was characterized by extensive warmth, with little-to-no terrestrial ice and with above freezing temperatures year-round globally. From that point of view the modern mean climate state, characterized by ice sheets at both poles is a climate aberration — only 5% of the past 100 million years has been spent in that state. The transition from the "Greenhouse World" of the Cretaceous and Eocene to the "Ice-House World" of today occurred in a stepwise fashion, with long periods with only orbitally-induced fluctuations around the long-term mean state, followed by stepwise climate shifts.

The climate system underwent the largest shift of the past 100 million years, near the end of the Eocene (~34 million years ago), from a world in which temperatures much below freezing were not felt within continental interiors or the poles—even in winter—(e.g., Feary et al., 1991; Sloan, 1994; Wolfe, 1994; Greenwood and Wing, 1995; Markwick, 1998; McPhail, 1999; Zachos et al., 2001), to a climate closer-to-modern with significant glaciation at one pole (e.g., Kennett, 1977; Miller et al. 1987; Zachos et al., 2001). While changes in ocean currents probably played some role in this climatic shift, a leading role for greenhouse gas changes has found substantial support from data and models (Huber et al., 2004; Stickley et al., 2004; Deconto and Pollard, 2003). This transition was rapid on geologic timescales, a modern sized Antarctic ice sheet (~1km thick) was emplaced on time scales of 10^4 years.

Subsequent climate changes, in the Miocene and Pleio-Pliestocene completed the transition to the modern world, by initiating global cooling and Arctic glaciation. While these 'mean' climate changes were associated with Earth's major boundary conditions (topography, concentrations of greenhouse gases) change, orbitally-induced changes in the top of the atmosphere radiative balance caused orbital band climate variability throughout the record (from at least the Cretaceous on). Because the long-term mean climate state of the modern world is in the "Icehouse" regime, these orbitally-induced perturbations cause climate to oscillate between two climate states, glacial and interglacial on time scales with strong periodicities in the precessional band. Both glacial and interglacial states are characterized by conditions significantly different than much of the past 100 million years, i.e. cold winters and high latitude ice.

Greenhouse Gases in the Cenozoic

Pearson and Palmer (2000) used boron isotopes to constrain sea water alkalinity, which, in turn, was used to estimate past greenhouse gas concentrations. They developed a 60 Myr record of pCO_2, which, surprisingly, matched Pagani et al's (1999) alkenone based estimate that there was no change in pCO_2 during the late Miocene. This same record also suggested much higher pCO_2 previous to 40 Mya, with ranges of 500 ppm to 4000 ppm. De La Rocha and DePaolo (2000) showed that long records of the variation of marine calcium isotopes might be used in conjunction with ocean pH records, such as boron proxies, might provide a second means of estimating pCO_2 through time. The middle range of those values and the general trend of increasing pCO_2 in the earlier parts of the record were generally in agreement with low resolution estimates of pCO_2 by Berner and Kothavala (2001) based on yet another independent technique using the carbon isotopic values (C^{13}) and the latest version of Berner's carbon cycling model GEOCARB III. Retallack (2001) synthesized a low resolution 300 my time series of estimated pCO_2, again showing high values during the early Cenozoic and the Mesozoic, in loose agreement with the results of the two previous studies. Retallack's proxy was "stomatal index" based on a normalized count of the number of stomata on ginko leaves. Royer et al. (2001), using the same proxy but with a different calibration and on different samples, reached opposite conclusions, estimating relatively low (near-present to 560 ppm) values of pCO_2 during the early Cenozoic. Royer et al.(2001) have recently reviewed the strengths and weakness of the various methods, but it is clear that this is a rapidly evolving area, and there is a divergence of interpretation of data.

Nevertheless, the correlation of possible high values of pCO_2 previous to 40 Mya and the high temperatures at that time have caused many scientists to draw causal relationships between the two. Consequently, for a portion of scientists studying climate change, conditions in the Eocene would represent one possible end state for global climate conditions, with the assumption that anthropogenic emissions of CO_2 are imminently triggering a long-term major shift in global climate. As discussed above in this Appendix, there is not currently scientific consensus whether atmospheric CO_2 is having this effect. Nevertheless, conditions in the Eocene represent a potential end state for climate change, and as such are reviewed here.

A.2.3 Conditions in the Eocene: One Potential End State for Global Climate

The interval from the late Paleocene (57.4 Mya) to the early Eocene (53.4 Mya (*Berggren and Aubry*, 1996)) is one of the warmest time periods in Earth history and contains some of the best evidence for warm-climate variability in the geologic record, as shown in high-resolution records (*Zachos et al*., 2001). Paleontological proxy data throughout the Paleocene-Eocene interval provide evidence of a "greenhouse" world: high-latitude continents were ice-free (*Zachos et al*., 2001), vertical and meridional temperature gradients in the ocean were small (*Shackleton*, 1986), crocodiles lived near the poles (*Markwick*, 1994, 1998; *Greenwood and Wing*, 1995), and plant and clay distributions indicate that terrestrial winters were mild and moist (e.g., *Wolfe*, 1978, 1985, 1994; *Robert and Chamley*, 1991; *Robert and Kennett*, 1992; *Gibson et al*., 1993).

Embedded within this interval is an abrupt and transient (~100 kyr) warming event (*Kennett and Stott*, 1991; *Zachos et al*., 2001), called the Paleocene Eocene Thermal Maximum (PETM), shown in Figure A-2. During this time, oxygen isotope proxy data indicate high-latitude warming of 6°-8° over less than 10,000 years (*Thomas et al, 2003*), with little tropical warming (*Zachos et al*., 2001; *Bralower et al*., 1995; Zachos et al., 2001). A global, continental and oceanic shift in δ^{13}C of approximately -2.5‰, coincident with the δ^{18}O change, is evidence of a major perturbation to the global carbon cycle (*Kennett and Stott*, 1991; *Koch et al*., 1992; *Lu and Keller*, 1993; *Bralower et al*., 1995; *Thomas and Shackleton*, 1996; *Bralower et al*., 1997; *Dickens et al*., 1997).

The large, rapid δ^{13}C shift has found its best explanation in the methane hydrate release hypothesis of *Dickens et al*. (1995, 1997), which relies on rapid warming of deep waters in order to generate a sudden degassing of methane hydrate to release methane into the atmosphere. The methane driven global C^{13} isotopic excursion at the PETM, that ushered in the Eocene, allows the correlation of terrestrial and oceanic records and the ability to establish rates of climate change globally with great precision (on the order of thousands of years) and the chance to explore how the climate system and carbon cycle respond to a sudden release of a greenhouse gas.

The PETM is considered by some (Zachos et al., 2001) to be the closest existing analogue to global warming associated with anthropogenic sources. The interval of greenhouse induced warming is on the order of 10^5 years and appears to have been limited by long time scale weather feedbacks, which are themselves closely tied in with changes in temperature and hydrology on continents. This, then, is the analogue that some scientists would use for global climate change over long times into the future.

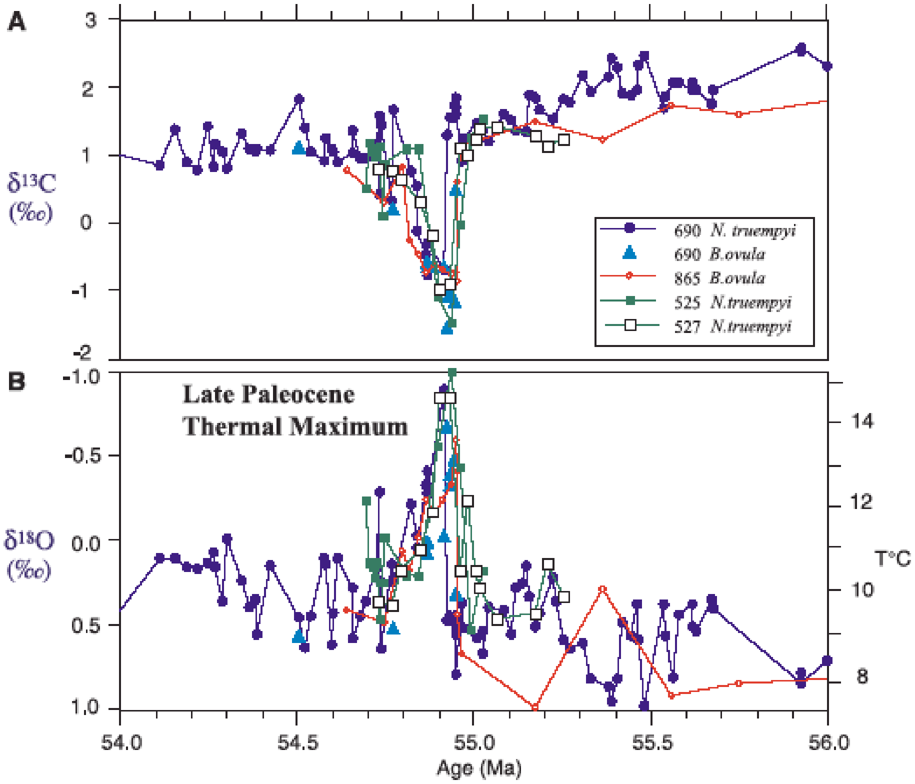

Figure A-2
Oxygen and carbon isotopic records of the PETM compiled by Zachos et al., 2001. The carbon isotopic records are consistent with a massive and sudden release of methane hydrate that initiates a massive global warming shown in the oxygen isotopes. The time scale of initiation as brief, but the warming lasts for on the order of 100,000 years. The time scale of subsequent cool is compatible with global weather feedbacks.

A.2.4 Paleoprecipitation in the Cenozoic, the Record of Drying

The consequences of such climate behavior on precipitation needs to be explored as a first step in understanding the implications of a global warming trend on Yucca Mountain. A compilation of quantitative paleoprecipitation estimates by Wilf et al. (1998) is useful for comparative purposes even though it does not contain any values in the Yucca Mountain region. This study suggests that from the variety of indicators discussed above there is some evidence of precipitation and associated soil moisture levels considerably higher than modern day values in the western US during the Eocene. The values shown in Table A-1 suggest that precipitation in the West was an order of magnitude higher in the Eocene than present day values.

The Copper Basin Flora of northeastern Nevada (~42°N, age ~40 Mya) captured part of the drying associated with the Eocene transitioning into the Oligocene, This flora contains a lake and streamside community including *Alnus, Acer, Amelanchier, Crataegus, Mahonia, Prrunus,* and *Salix*, as well as a conifer-deciduous hardwood forest containing *Sequoia, Pseudotsuga, Sassafras, and Ulnus* (among others). At the estimated paleoelevation of 1200 m, the climate was ‘cool temperate’ and characterized by a mean annual temperature of 11°C and annual rainfall of 1200 to 1500 mm.

Table A-1
Interpretation of precipitation from indicators by Wilf et al. (1998).

Location (approx age in Ma)	Mean Precipitation (mm)	Error (positive, negative) mm
Bear Paw (49-51)	1300	561, -392
Sepulcher (50-51)	1360	588, -410
Camels Butte (53-55)	1570	676, -472
Chalk Bluffs (50-52)	1600	689, -481
Green River (45-48)	840	362, -253
Kisinger Lakes (49-50)	1100	474, -331
Wind River (50-51)	1040	448, -313

A compilation (using techniques independent of those in Wilf et al., 1998) by Sheldon and Retallack (2004) shows a clear drying trend throughout the West progressing from the Eocene into the Oligocene, with declines of 30-200% over several million years (Figure A-3).

Before about 15 Ma, the western US was wet with a humid climate and precipitation well-distributed throughout the year (Axelrod, 1977). The extensive deciduous forests throughout the region required high levels of summer precipitation (ca.400 mm in June-July-August; Axelrod, 1992), like similar forests in the modern east and southeastern U.S. The middle through late Miocene (16-5 Ma) mark a much wetter than modern Western climate within a generally warmer earth system. The Miocene/Pliocene boundary is roughly defined by the disappearance of the Miocene deciduous ‘exotics’ from coastal northern California (Heusser, 2000) and the beginnings of the modern arid era. Large numbers of Miocene plant macrofossil localities throughout the West make this interval one of the best documented paleoclimate transitions in the Cenozoic (Axelrod, 1977; Graham, 1999). The middle Miocene wet and warm extreme (pre 15 Ma, Axelrod, 1968, 1977; Wolfe, 1985, 1994; Graham, 1999) represents a fundamentally different water cycle in western North America, especially the U.S. West. Whereas the modern West is arid at all latitudes south of ca 47°N, the Paleogene and Neogene West was covered with extensive deciduous and mixed deciduous-conifer forests that required extensive summer precipitation, probably greater than 400 mm (16 in) in the summer months alone. In contrast, the modern Pacific Northwest, California, and Nevada experience Mediterranean (summer-dry) conditions, with peak precipitation in the winter months. A weak monsoon brings some summer precipitation to the Southwest, sufficient to support forests at altitude. Middle Miocene forests, however, were distributed at all altitudes in the west. Evidence for extensive summer-wet conditions extends as far south as southern Nevada (Axelrod, 1992) and deciduous forests needing summer precipitation extended northward into Alaska (Wolfe, 1985). The Miocene deciduous, summer-wet forests disappeared in a long climate transition that began after 15 Ma and continued to about 5 Ma. After 5 Ma, floristic assemblages resemble modern plant distributions (Axelrod, 1977).

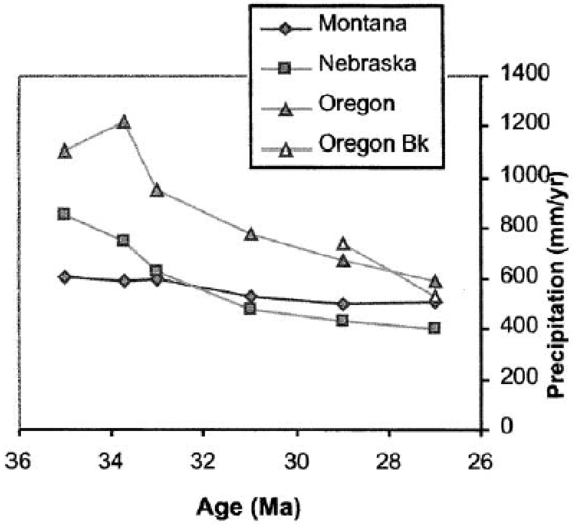

Figure A-3
Estimates of Paleo-precipitation in the West from Sheldon and Retallack (2004).

Stable isotopes of hydrogen in silicates may also be interpreted as revealing past climate information for the area near Yucca Mountain. Winograd et al.(1985) found that hydrogen isotope ratios (δD) in calcite fluid inclusions became progressively depleted in the heavy isotope from 2.5 million years to the present. They interpreted this as due more to the progressive uplift of the Sierras, and increasing rain-shadow effect than to temperature. Their data are consistent with those of Arehart and O'Neil (1993) who reported δD values of hydrogen in supergene (infiltrating water produced) alunites from Nevada. Their data span 29 to 5.3 million years ago, and show a 25 permil decrease in δD from 15 to 8 million years ago. These data suggest that southern Nevada climates during the mid Miocene (15 million years ago), were a few degrees C warmer than today's climates.

Hence, it is seen that a number of factors may have led to the change from a more temperate climate in the western US to the more arid conditions of today. Without a firm understanding of the causes of aridification of the West, future predictions are speculative. Some factors that led to this pattern of change are understood. Changes in tectonic boundary conditions undoubtedly were a major factor causing the disappearance of wet summer conditions. However, the nearby uplift of coastal mountain ranges was likely not the driver of the aridification of the West. Uplift probably occurred subsequent to the major climate changes associated with the aridification (e.g. Unruh, 1991). Further evidence that uplift of mountains was not the cause of the transition is the disappearance of summer wet floras from both sides of the uplifting Sierra Nevada (Heusser et al., 2000; Lyle et al., 2003). If the rain shadow was a primary cause of the transition, the western slope of the Sierra should have gotten wetter, not drier. While the rain shadow may not have been the cause of the aridification, its development did contribute strongly to the modern pattern of very dry desert basins and wetter mountain tops. It is clear from Figure A-4 that the West as a whole is generally dry, thus orogeny is not the sole explanation for the aridification of the West.

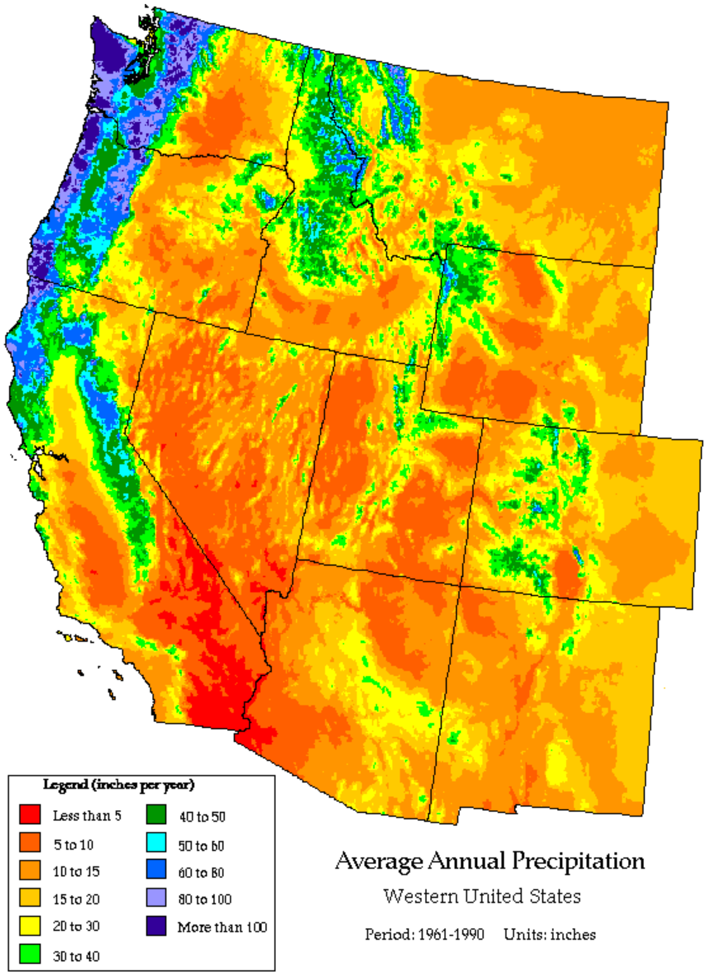

Figure A-4
A map of annual average precipitation in the West provided by the Western Regional Climate Center of the Desert Research Institute.

There is now substantial evidence that the inter-annual and inter-decadal variability of precipitation in the U.S. West is correlated with the variability of sea surface temperatures (SSTs) in the Pacific Ocean. For instance, Cayan et al. (1998) showed that precipitation in the southwest of the US was positively correlated with SSTs in the eastern equatorial Pacific and eastern Pacific subtropical gyre for the period 1900-1991. Warm SSTs in those oceanic regions are associated with anomalously heavy precipitation in the western U.S. in strong El Nino years (e.g., Simpson, 1983). More recently, McCabe et al. (2004) have demonstrated that 52% of the variance in multi-decadal drought frequency in the contiguous United States can be linked to the combined effects of the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO).

There also exists an important interaction between ENSO and the PDO: ENSO teleconnections with Western precipitation are generally strong when the PDO is negative and generally weak when the PDO is positive (McCabe and Dettinger, 1999). Additionally, monsoon flow over the western US is strong when El Nino conditions coincide with the positive PDO phase and weak when La Nina conditions coincide with the negative PDO phase (Castro et al., 2001). Further defining connections between the Pacific and continental precipitation, Lau et al. (2002) reported that consideration of variability not only in tropical but also North Pacific SST improves seasonal predictability of the North American monsoon.

New analyses have been performed of modern correlations between SSTs and precipitation, using the ERA40 re-analysis dataset from the European Centre for Mid-Range Weather Forecasting (http://www.ecmwf.int/research/era/). These results are shown in Figure A-5. Monthly anomaly surface temperature and total precipitation are correlated. In (a), precipitation in a latitude–longitude bin including Yucca Mountain are correlated with global temperature fields. Figure A-5 conveys the regions in which SST changes strongly affect precipitation anomalies in the West. The spatial pattern that emerges is extremely similar to already identified ENSO and PDO-type SST anomalies. This strongly suggests that precipitation at Yucca Mountain will be sensitive in changes to the tropical Pacific and especially ENSO.

The Pacific ocean-atmosphere system is governed by a delicate balance of dynamical feedbacks raising concern about its stability to changes in external forcing. In the equatorial Pacific, the prevailing easterly surface winds drive an east-west tilting of the thermocline. The tilting causes cool sub-thermocline water to upwell in the east. The resulting gradient in sea surface temperature (SST) between the Cold Tongue in the east and the Warm Pool in the west drives an east-west overturning circulation in the atmosphere, the Walker cell, which enhances surface easterlies and produces further upwelling. This positive feedback, controls both the time-mean state and the interannual (ENSO) variability of the tropical Pacific. Because instability lies at the heart of tropical Pacific climate, it has been proposed that the region's climate could undergo major, long-term reorganizations, which could strongly modulate the global hydrologic cycle. In particular, theory indicates that any changes acting to weaken the 'Bjerknes' feedback might lead to reduced ENSO variability and eventually to its complete shutdown. In these circumstances, the system collapses onto a permanent El Niño-like state with a weak thermocline tilt, little or no upwelling in the east, and a small sea surface temperature (SST) gradient along the Equator. The climate impacts observed during a modern El Niño event, including higher global mean temperatures, increased heat export to the extratropics, and continental warmth over parts of North America—and crucially, increase in summer rainfall in the West—would presumably become a permanent fixture of global climate (Molnar and Cane, 2002). A permanent El Niño could explain features of past climates such as high latitude warmth and less arid conditions in Africa and the American West, and provides a possible amplifying mechanism for future global warming. Assessing the robustness of the tropical Pacific climate is thus a key issue for understanding both past and future climate change. The higher SST expected in the middle Miocene eastern tropical Pacific should have provided a major water (and energy) source for the North American monsoon system.

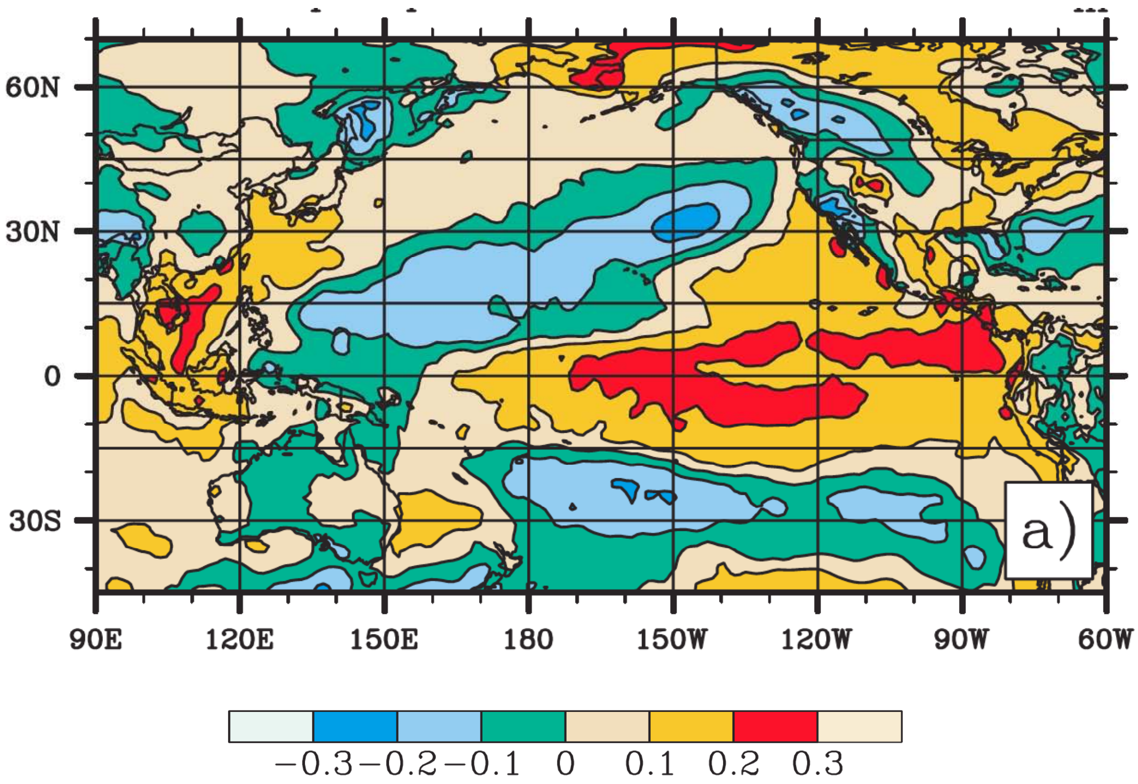

Figure A-5
Correlation of surface temperature changes with precipitation within a grid cell that includes Yucca Mountain. Data are taken from the ECMWF 40-Year Reanalysis product. Precipitation variations clearly project onto a pattern that resembles the ENSO teleconnection pattern.

It is therefore quite likely that major changes in tropical Pacific ocean-atmosphere dynamics (Ravelo et al., 2004) played a role in the drying of the West. If so, this is a major source of uncertainty in Yucca Mountain climate going into the future, as it has been proposed by many researchers that the dynamical regime that has persisted in this region for the past 3 million years is poised to change in a global warming world (Fedorov and Philander, 2004), but there is far from universal agreement on that prediction (Huber and Caballero, 2003). Projections into the future therefore are seen to result from the complex interactions of a number of phenomena, the contributions and relative importance of all of which has not yet been fully established.

A.2.5 Quaternary Considerations

Figure A-6 illustrates global climate changes as recorded by the stable oxygen isotope ratios in marine microfauna during the Pleistocene Epoch. The Pleistocene is often referred to as the glacial age. Lower values of δ^{18}O (i.e., more depleted in the heavy isotope—note inverted vertical scale) indicate times of less ice on continents, and hence higher global temperatures. These represent interglacials. Glacial periods are recorded as more positive δ^{18}O values. Ages of the deep-ocean sediments have been assigned by radiometric and paleomagnetic dating. Spectral analyses of the δ^{18}O variations in the time domain show frequencies that correspond to periodicities of the so-called Milankovich insolation cycles. Convincing evidence supports an astronomically-driven hypothesis for glacial-interglacial recurrences on a 100,000-year time scale as recorded in deep sea cores and ice cores. Periodicities appear at 100,000 year, 43,000 year, 24,000 year and 19,000 year time intervals, corresponding to periodicities of the Earth's orbit eccentricity, precession and tilt with respect to the orbital plane (Imbrie and Imbrie, 1979). Thus, the astronomical forcing of glacial periodicity appears to be related to periodic changes in the seasonal and latitude distribution of solar energy impinging on the Earth. Yet the 100,000-year cycles of $\delta^{18}O$ in foraminifera are not exact images of each other, indicating that other factors as well control the Earth's long-term climate changes. What triggered the initiation of these cycles some three million years ago, and when these cycles will terminate is controversial, although changes in ocean circulation were likely involved.

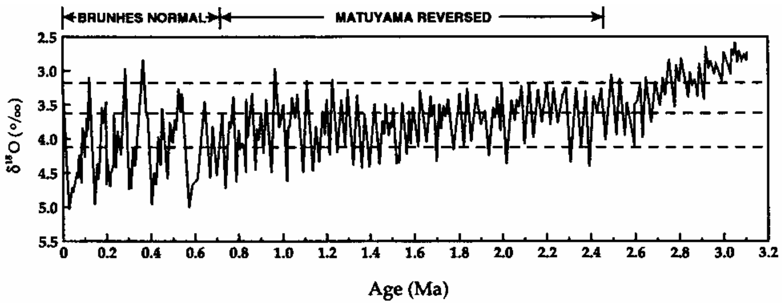

Figure A-6
$\delta^{18}O$ variations in forminifera from deep-sea sediment cores. More positive values indicate cooler times when greater volumes of ice were on the continents.

Cycles similar to those identified from deep sea cores and polar ice cores, with a near-matching chronology appear in $\delta^{18}O$ variations in vein-filling calcite at Devil's Hole near Yucca Mountain (Winograd, et al., 1992), suggesting that these astronomical cycles affected the climate in the Yucca Mountain vicinity as well. Climates in other continental areas were evidently affected also. For example, Colman et al. (1995) illustrate variations in diatom silica contents from Lake Biakal that show correspondence to orbital periodicities. Using Mg/Ca, Lea, Pak and Spero (2000) created a 500 kyr time series of planktonic foraminiferal Mg/Ca ratios in the eastern and western Pacific that demonstrate 4 crucial points: (1) glacial tropical SSTs were about 3° cooler than nonglacial values, (2) the east-west gradient in Pacific tropical temperatures was close to modern, (3) the troublesome Devils Hole δ_c record was in phase with the Mg/Ca record, (4) Antarctic records temperature records based on deuterium excess, were also synchronous with this tropical Pacific record. The latter two records directly linked the tropical climate with extratropical climate. Thus, the Lea et al record clearly demonstrates strong linkages between climate in the Yucca Mountain region and orbital forcing, but also raises the possibility that these linkages are mediated via the tropical Pacific.

The current Quaternary glaciation is characterized by intervals of extensive ice cover in the northern hemisphere at periods of glacial maxima, and warmer, interglacial periods when the ice cover is much reduced. The most recent glacial maximum was 21,000 - 18,000 years ago; the previous about 135,000 years ago. Recent research has begun to provide more detail, indicating many sudden, short-duration (10's-100's years) cold events and warm (interstadial) periods superimposed upon the overall trend over the geological timescale (OCRWM, 2000). Smaller but still significant climate changes, “mini ice-ages,” have occurred over hundreds of years in the historical record.

As revealed by Greenland ice core records (Figure A-7), the past 8,000 years have experienced a less variable climate then at any time in the past 100,000 years. From records such as this, it appears at least possible that the extremely variable glacial-interglacial cycles were approaching a new state by 8 ka even in the absence of anthropogenic influences.

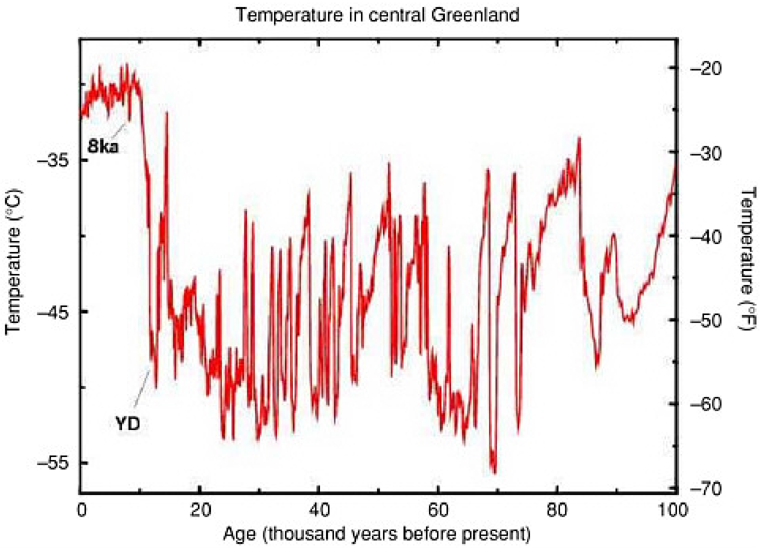

Figure A-7
Proxy-based temperature estimates from Greenland. Taken from NAS (2002).

This observation renders further uncertainty in the simple assumption that the past record of glacial-interglacial transitions is the most likely model for future change. Recorded history extends back only part way within this present-day so-called “post glacial” period. However, this amicable climate existed on Earth during perhaps only 10% of the past million years. It is unlikely to be a coincidence that this period corresponds exactly to the period during which human civilization developed. It appears that human societies and modern climate have co-evolved, that they are a coupled system and it is unlikely to be an accurate description of their coupled behavior to consider changes in one without changes in the other.

Even during the past 8,000 years of post glacial climates, the Earth has undergone extended times of somewhat cooler and somewhat warmer climates (See Figure A-8). A bridge between time periods in which we are limited to using only climate proxies and the past 100 years or so of instrumental records is provided by using historical records, primitive instrumental records, and climate proxies to reconstruct climate variation over the past millennia. The arduous task of compilation and statistical analysis of databases of important climatic parameters from these records has been carried out in large part by Briffa et al. (1998), Mann et al. (1998), and Jones et al. (1998).

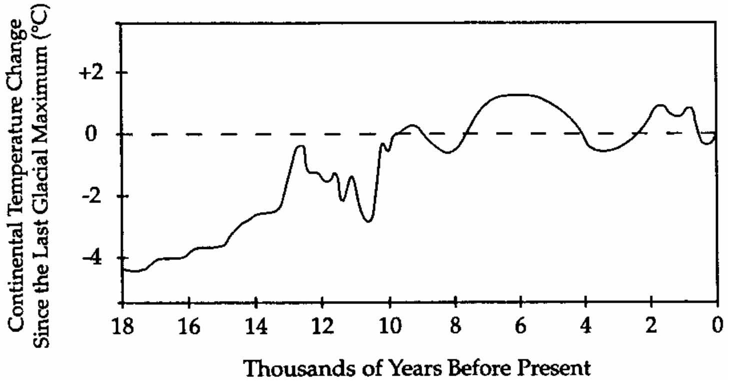

Figure A-8
Generalized global temperature trends since the last glacial maximum (after Crowley, 1996).

Crucial lessons have been learned from these synoptic analyses. Oscillations of observable climatic importance today like El Niño and the North Atlantic Oscillation (NAO) are measurable in climate proxies such as tropical corals and European tree rings and make up a large part of the variability in past climate time series. Volcanic eruptions and inferred solar variability are also found to have significant but variable cooling effects that are reflected in historical records of the time (such as the "Year with no summer"). Crowley's model, when driven by forcing derived from proxies for volcanic eruptions and solar variability over the past millennia, matched these temperature proxies, giving a critical line of evidence for the ability of climate models to respond correctly to forcing (Crowley, 2000).

In a further extension of the technique of checking climate proxies against independent historical or archaeological records, Cullen et al. (2000) found a dramatic increase in dust concentrations in marine cores taken offshore directly downwind of Mesopotamia at 4025±125 BP. This dust maxima indicated a 300 year long drought in the region, at a date that matched exactly the timing of the fall of one of the great civilizations in the region, the Akkadian Empire. Even further back in time, extending all the way to 12,000 BP, Weiss and Bradley (2001) have described linkages between high resolution deep sea climate records with archaeological, historical, and terrestrial climate records to show that many of the events in the early history of civilization were driven by climatic variations.

Hence, it is clear that future climate change in the Yucca Mountain region may be driven by a number of phenomena. The relative importance of these phenomena, and indeed whether some of them are acting at all, is open to interpretation. Clearly, given the uncertainties in the phenomena driving potential climate changes, caution must be exercised in over reliance on any one interpretation of the climate system.

A.2.6 Additional Sources of Climate Variability

In addition to these major phenomena driving the climate, due consideration is necessary of solar and volcanic drivers for climate.

Solar

Because the Sun is the source of virtually all of the Earth's energy, variability of its output on a scale of decades to centuries, or even millennia would be of interest in forecasting future climates. Changes on a much longer, solar evolution time scale, are theoretically likely, but not considered here. Long-term (on a scale of billions of years) changes in solar energy output are probably not important if on these time scales, the Earth's climate is regulated by global tectonic and sedimentation processes (Kasting and Toon, 1989, Berner, 1991).

Correlation of climate with sunspot occurrences has been considered in the literature. Kerr (1995) reviews briefly the history of correlations of climate with 11-year sunspot cycles. He summarizes recent reports of observations of pressure increases and greater ozone production with increased solar energy output. He also notes that solar energy output was minimal during the Little Ice Age of the 17th century. Most who are familiar with the field agree that solar energy differences shown in the 11-year cycles are of minor importance in affecting global climates (e.g., Covey, 1996). However, Haigh (1996) noted that solar energy arrives in specific wavelengths, which can induce specific photochemical reactions, which in turn may affect the hydrological cycle, planetary waves, or atmospheric circulation. Haigh tested this with an atmospheric circulation model, and concluded that the 11-year solar cycle did produce shifts in storm tracks similar to, but smaller in magnitude than, those observed in nature. For the present study this source of weather variability was considered to be of secondary importance. Crowley and Kim (1996) found statistically significant positive correlations between solar irradiance changes and northern hemisphere temperature changes over the past 400 years. They suggest that solar energy output may be responsible for a significant portion of the temperature changes during the Little Ice Age (AD 1350 to 1850). A stronger energy variation of solar origin comes from solar flares (Damon, 1992). Projections of the periodicities of solar-flare output indicate that solar-energy changes will enhance the greenhouse effect well into the next century.

Volcanic Activity

Major volcanic eruptions can affect climate, but the effects last only as long as the volcanogenic aerosols remain in the atmosphere. The particulates primarily responsible are dust particles, carbon dioxide and sulfur dioxide. Volcanogenic carbon dioxide is evidently part of the weathering/plate-motion process regulating the Earth's climate on a long time frame. Excess carbon dioxide can trap extra heat in the troposphere. On a shorter time scale, volcanogenic sulfur dioxide, which quickly forms sulfuric acid aerosols, has a reflective, cooling effect on Earth's climate. These aerosols and the dust particulate ejecta are nuclei for condensing water, and return to earth as precipitation or dry fallout. Owing to the relatively short residence times of sulfur dioxide, sulfuric acid and dust aerosols in the atmosphere compared to that of CO_2, the cooling effect is brief. Thus, the intensity of their cooling effect depends on the amount of volcanic ejecta. It is possible that the largest eruptions could affect climate sufficiently to reduce growing-season temperatures for a year, possibly more, greatly reducing global food production.

Figure A-9 is based primarily on data in Newhall and Self (1982). It includes explosive eruptions of known intensities recorded historically during the past 500 years. If the volcanic intensity distributions in the future can be predicted from past eruptions, volcanic events ten times the size of Pinatubo or Tambora can be expected to occur once or twice per millennium.

In addition to potentially disastrous impacts on agriculture, the cooling effects of these major volcanic eruptions would reduce evapotranspiration and hence increase net infiltration at Yucca Mountain. These infiltration pulses would be brief, but possibly significant. Figure A-9 illustrates numbers of historic volcanic eruptions according to volume of ejecta (complied from a variety of sources referenced herein).

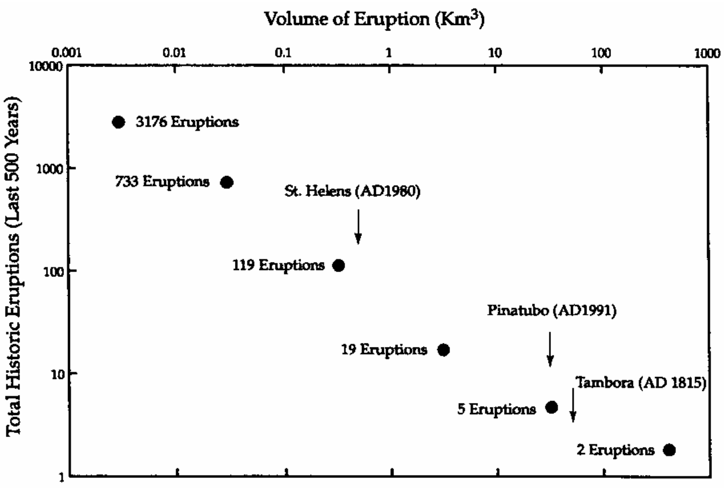

Figure A-9
Numbers of historic volcanic eruptions according to volume ejecta.

The eruption of Mt. Pinatubo in the Philippines in 1991, evidently caused slightly cooler temperatures for a year or two after its eruption. The residence time of SO_2 in the atmosphere is short compared to that of CO_2. The consequence of this is that industrial activity, which produces both CO_2 and SO_2, places molecules into the atmosphere that are masking their opposite effects on the Earth's energy balance (Schwartz and Andreae, 1996; Wigley, 1995; Mitchell, et al., 1995).

A.3 Paleoclimate Studies in the Yucca Mountain Region

EPA (2001) said the following about their basis for climate changes in preparation for issuing 40 CFR 197:

> "Southern Nevada and the Great Basin experienced such dramatic changes, which, together with lower temperatures, led to aquifer recharge and the filling of many closed basins with extensive lakes. Such changes are evident in geologic features of the region. Variations in lake levels extending back into the last glaciation are best known; they are generally well-dated and have been studied in many areas of the western United States. Observed changes are well supported by a variety of biological evidence, particularly that obtained from the analysis of packrat middens, which contain discrete samples of local vegetation in the vicinity of the packrat nests from particular time periods in the past. For example, when lake levels were high, vegetation was generally more extensive; some areas that are arid today were forested. This can be seen from the packrat middens, where vegetation can be related to past time periods."

EPA further elaborated:

> "Hydrological changes in the arid western United States do not coincide in detail with the record of continental ice volume changes. However, it is clear that high lake levels were present when the Laurentide Ice Sheet was extensive and that water levels fell in association with deglaciation. As noted by Smith and Street-Perrott, "more than a hundred closed basins in the western United States contained lakes during the Late Wisconsin [the last episode of the ice ages], 25,000 to 10,000 yr B.P. [before present], but only about 10 percent of the lakes are perennial and of substantial size today...." Even in today's hyperarid Death Valley, there is evidence that an extensive lake occupied the basin between 21,500 and 11,900 years ago."

Larsen (2003), specifically focused on the Amargosa River, has stated that

> "In the Tecopa basin, along the ancestral Amargosa River valley, perennial lakes existed from ~1 Ma to >0.76 Ma, from 0.76 to <0.62 Ma, and at least twice after 0.62 Ma. By surface area, the greatest lake existed just prior to 0.62 Ma."

Thompson et al. (1999) described reconstructions of the flora at Yucca Mountain during the late Pleistocene, including the last glacial maximum (21 to 18 ka). Thompson et al. (1999) concluded that most of the modern analogues for late Pleistocene middens from the Yucca Mountain region lie in the steppe and woodland regions of the central Great Basin, and to a lesser extent, the Colorado Plateau.

NAS (1992) noted that

> "…very few closed basins [in Nevada] possess wave cut terraces and, therefore, it is unlikely that they supported pluvial lakes. This observation also applies to basins in adjacent California. The only known exceptions are lakes that were fed by runoff from the east slopes of the Sierra Nevada and Transverse Ranges (such as Pluvial Lakes Mojave and Searles), and a small basin on the northwest end of the Sheep Range, ca. 100 km east-southeast of Yucca Mountain."

Nevertheless, NAS concluded that "the extensive Wisconsin-age spring deposits in the larger valleys of southern Nevada attest to a considerable expansion of wet-ground habitats during the last glacial age."

Some of the data considered by NAS (1992) are shown in Figure A-10. In particular, Forty-Mile Wash exhibits "unequivocal records of wet-ground habitat in uplands where none now exists." These wet grounds are identified as perennial water bodies, existing in the early Holocene (NAS, 1992).

Direct measurements of extreme precipitation events that occur very rarely are often not available. The paleoflood literature reports the manifestations of these events (Martínez-Goytre, et al., 1994; Ely, et al., 1993; Enzel, et al., 1993). These indirect records of paleofloods allow the estimation of storm magnitude and statistical recurrence intervals.

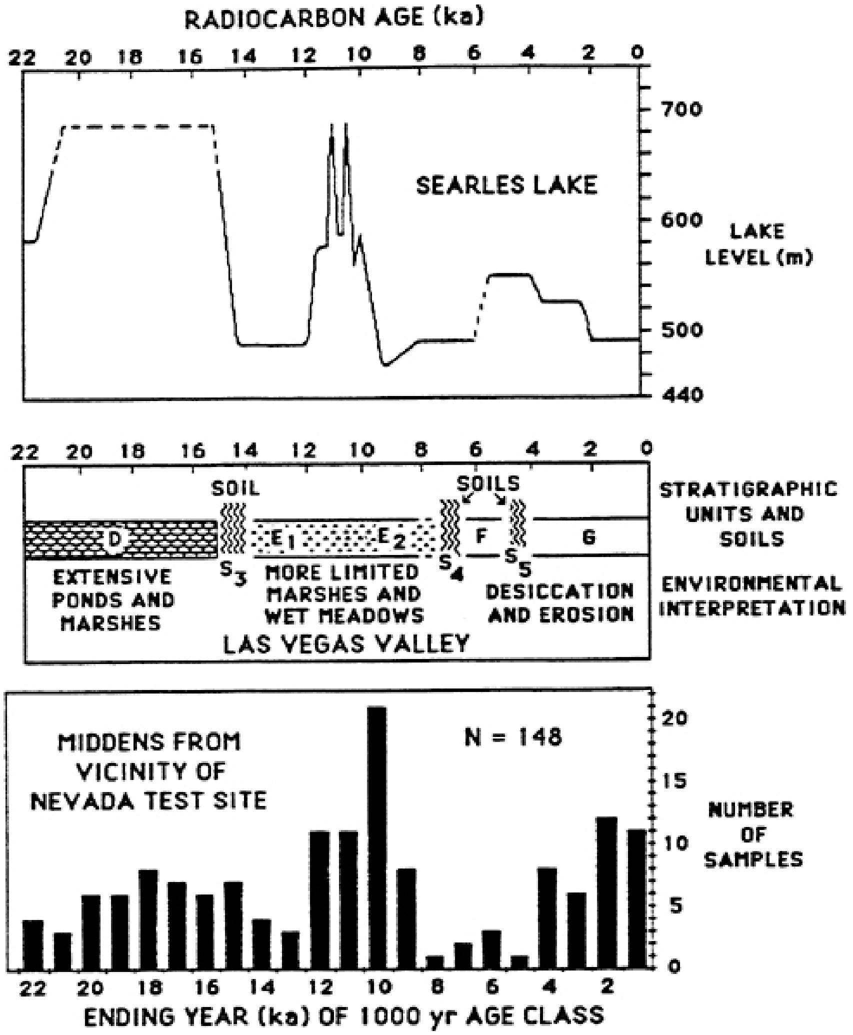

Figure A-10
Comparison of paleohydrologic chronologies from the southern Great Basin with the temporal distribution of midden samples from Yucca Mountain and vicinity (NAS, 1992).

A.4 Predicting the Future

The paleoclimate information forms the foundation of understanding of the current climate, and provides a basis for projecting climate into the future. Two approaches have been taken in an attempt to characterize future climate changes. One is to look to the past when the Earth experienced conditions similar to those assumed to happen in the future (i.e., the paleoclimate analogue approach). The other is the employment of numerical climate models that attempt to simulate the Earth as a dynamic system. Both approaches have their advantages and limitations. However, if both are mutually consistent in their scenarios, greater confidence in their predictions is realized.

It is improbable that, except for brief intervals, the Earth's climate during the next 1000, 10,000, 100,000 or 1,000,000 years will replicate that during human-recorded history. As described above, the geologic record reveals major divergences from the present climate. These differences from present climate are better understood in terms of their effects on geography, flora and fauna than in terms of their causes, although viable hypotheses are available to explain causes.

Significant improvements have been made in models, and while they are far from perfect, and not necessarily better than a paleoclimate analogue approach, they do provide useful constraints on future system behavior, especially when combined with the paleoclimate analogue approach. In this section what climate models can and can not do well is summarized and then the paleoclimate analogue approach is detailed.

It is important to note that using analogues from further back in Earth's history amounts to making assumptions about the relative importance of climate change forcing factors (i.e., greenhouse gas changes vs. orbitally-driven insolation perturbations). These assumptions are not sufficiently grounded in certain knowledge to be characterized as more than arbitrary at the present time.

A.4.1 Numerical Climate Models

General circulation climate models attempt to simulate present, past and future climate. These models operate on the same principles as weather-forecasting models, in that they apply the physics of solar heating of the atmosphere, continents and oceans, the exchange of heat and mass between oceans and atmosphere, the circulation of water and air masses, and heat and mass exchange. In these models seasons change, and water evaporates and precipitates. In principle, these models could simulate the climate system as an artificial alternate Earth. In practice, the available computing power (they presently run on workstations and super computers) limits spatial resolution, and some important details of atmospheric dynamics. Although the day-to-day behavior of the weather in temperate zones is not responsive to long-range forecasts, the general trends of seasonal changes are predictable. It is still not possible to predict with certainty that next winter will be unusually cold or wet, but probabilities can be stated based on past experience. In the case of very long-range predictions, long-term climatic trends of the past and GCM outputs are called upon to estimate future climates and climate changes.

In the past decade, climate models have grown in complexity (to include full representations of the atmosphere, ocean, sea ice, land surface, and vegetation) as well in accuracy. These models have seen wide application for predicting current climate and climate change (IPCC, 2001) over the next several hundred years. These models form the basis of international agreements on climate change. As shown in Figure A-11, the current generation of models does a credible job of reproducing observed distributions of precipitation, including in the arid West. For future climate predictions, these models are forced with changing boundary conditions that are fixed based rules, i.e., assumption about the future evolution of societies, economies and ecosystems.

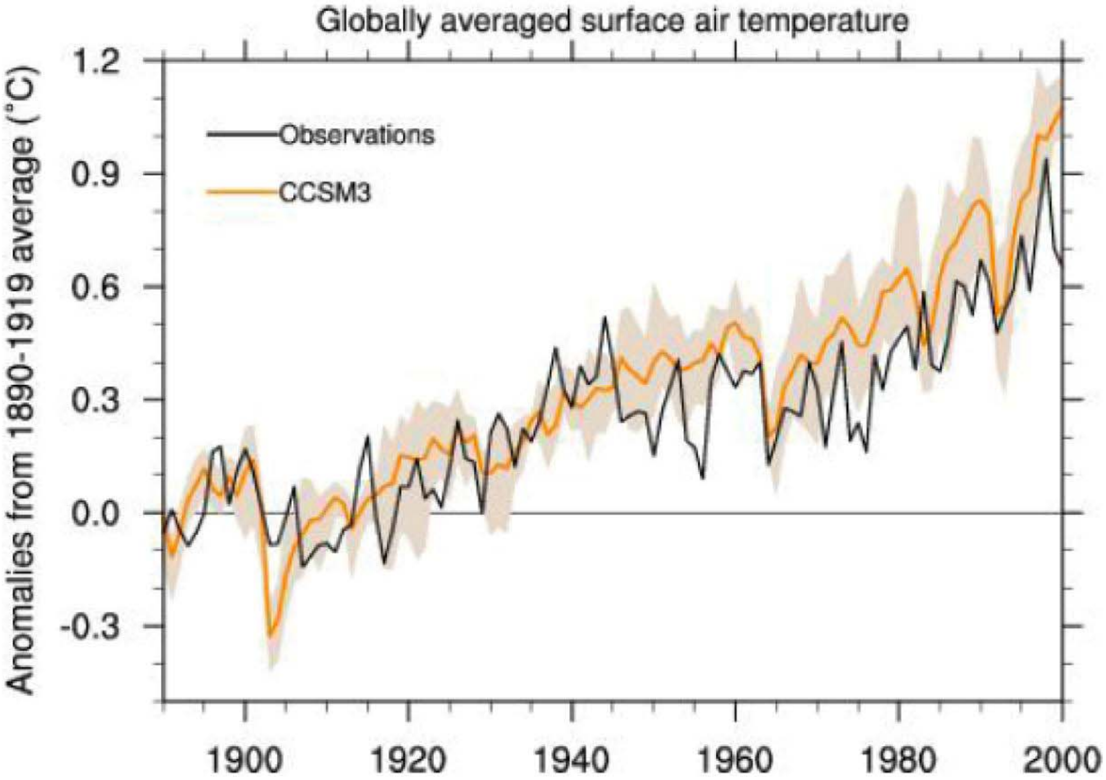

Figure A-11
Global mean temperature anomaly produced by the CCSM3 climate model as compared observations. Theses simulations include the effects of solar variability, volcanic activity and greenhouse gas concentrations.

In future climate change applications, scenarios for alterations of boundary conditions (i.e., greenhouse gas concentrations) are decided upon by international scientific bodies (i.e., the IPCC) and the sensitivities of a wide array of models are explored as a function of these preset scenarios. IPCC (2001) argued that warming has been occurring for the past century and that it will continue until polices are enacted to reduce anthropogenic emissions of greenhouse gases or some other means are found. The time scale over which a return to 'normal' conditions may occur following a global warming trajectory is a matter of current scientific inquiry. If past global warming events and existing knowledge of the feedbacks that returned conditions to normal are any indication, the time scale may be on the order of 100,000 years.

Changes in mean climate state from a NCAR CCSM simulation of future climate change is shown in Figure A-12. This simulation is based on a scenario of future boundary condition changes and has been carried out to levels of carbon dioxide concentration assumed characteristic of the next several hundred years, 1120 ppm. This is also a level roughly equivalent to that estimated to the Eocene.

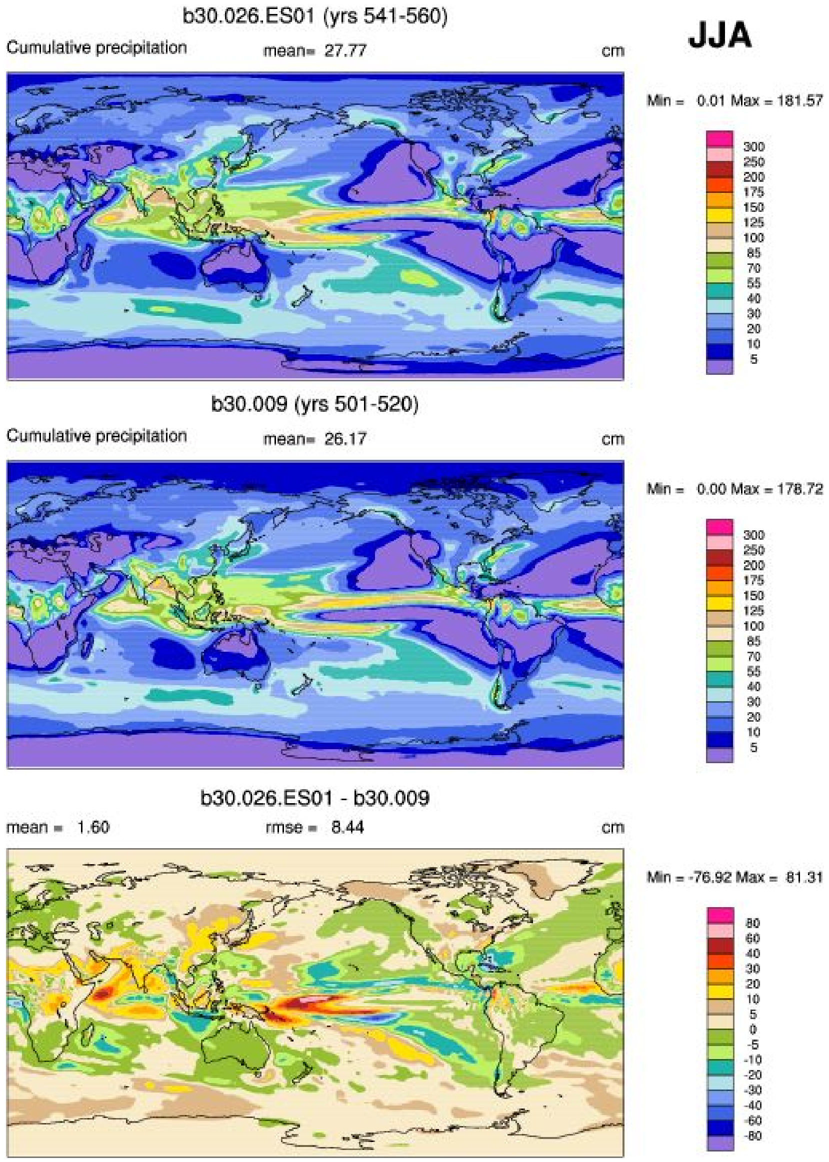

Figure A-12
Summer season average precipitation results from the CCSM3 control runs compared with observations. Top are model results. Middle are observations. Bottom is the anomaly. In the western US the model has a slight dry bias. These simulations were conducted by NCAR as part of the fourth IPCC report.

Interestingly, the climate model shows an insignificant change in mean precipitation (seasonally, and annually) over North America even at relatively high (1120 ppm) carbon dioxide concentrations that cause substantial increases in temperatures globally. This result varies somewhat from model to model. As discussed above on paleoclimate analogues, this result does not appear to agree with an Eocene analogue, which may indicate a deficiency in either approach or simply that CO_2 was not the only driver of the climate changes between the Eocene and modern.

This result illustrates an additional source of uncertainty. Even if a particular scenario for a global climate trajectory is accepted, there is uncertainty about the impact of that change on precipitation in the western US in general, and Yucca Mountain in particular.

One of the major limitations of using a global climate model to predict changes at a specific location is the discrepancy in scale between the smallest resolved scale of a climate model (e.g. ~2°x2°) and the scale of interest (~10km x 10km). One way to address this discrepancy may be to use a regional climate model, which employs the same sort of physical treatment as the global scale model but operates at a much finer scale (fed at its boundaries by output from a global scale model). Whereas temperature is a relatively smooth field, which may allow even a global scale model to produce meaningful results when applied at finer scales, precipitation is variable in both space and time, thus necessitating a fine scale model to make accurate predictions at smaller scales. Models are just approaching the level of detail necessary.

In the past several years, a suite of studies performed using different models by different groups have been applied to the climate and hydrological cycle of the West with a focus on California and Nevada (Snyder et al., 2002). These studies suggest that the high resolution associated with these models leads to significant improvements of the ability of climate models to predict precipitation when compared with point observations collected at individual weather stations (Snyder et al., 2002). An explicit comparison between such simulations and the extensive records collected in the Yucca Mountain area does not appear to have been published.

This same model configuration has been applied to both future global climate change and past climate change (in the Holocene). The model is able to simulate important aspects of Holocene climate as derived from paleoenvironmental proxies, which gives some faith in its ability to predict climate change as well as modern climate (Diffenbaugh et al., 2004). When applied to a future climate change scenarios with doubled carbon dioxide values, the simulation shows very little change in seasonal or annual mean precipitation in the Yucca Mountain region.

Thus, it would appear both from the global and regional climate model perspective that the consequences of future global warming on precipitation at Yucca Mountain are ambiguous, and more importantly there is uncertainty about increased runoff or infiltration given that model predicted temperatures may be warmer and precipitation may be decreased.

This leaves unanswered whether there will be substantial changes in extreme weather events, such as flooding. Changes in extreme weather are widely conjectured to be associated with global warming (Easterling, 2000), although evidence to that end is equivocal. Furthermore, there do not appear to be any extant models suggesting an increase in flooding or other factors that might affect infiltration as a function of global warming.

A.4.2 Conflicting Evidence in the Paleoclimate Record

The DOE uses the following information to estimate climate states in the Yucca Mountain region for the next 10,000 years (BSC, 2004):

> “To forecast the future climate conditions at Yucca Mountain, the following types of paleoclimate records, representing different time scales, were used: (1) regional records

> of stable isotope $\delta^{18}O$ fluctuations from Devils Hole, Nevada, and microfossil data from Owens Lake, California; (2) vegetation assemblages recovered from local packrat nests (i.e., midden); and (3) global records of an earth-orbital clock of precession and eccentricity and Vostok (Antarctica) ice core isotopic compositions. … The global records show that climate is cyclic over 400,000-year periods.
>
> "The timing of the climate intervals for the next 10,000 years is forecast on the basis of theoretically supported assumptions:
>
> - Climate conditions are …: (a) cyclic, (b) can be timed with the earth's orbital clock, and (c) repeat themselves in a predictable way.
>
> - The time of the transition from marine isotope stages 11 and 10 … is selected as the analog to estimate climate for the next 10,000 years.
>
> - Ostracode species assemblages from the Owens Lake record for this time period and the sediment accumulation rate are used to determine the nature and timing for the three future climate states… ."

Evaluations of climate at Yucca Mountain for the next million years are far from clear, and expert opinion is far from unanimous (see, e.g., DeWispelare *et al.* 1993). However, several lines of evidence reveal a pattern of past climate change with probable triggering mechanisms. These mechanisms will continue into the future, and here it is assumed that the climate system will respond as in the past.

DOE notes the following when attempting to establish future climate states over the next several hundred thousand years (BSC, 2004):

> "The technical basis for forecasting climate involves four key scientific assumptions (USGS 2001a, p. 19):
>
> - The climate is cyclical; past climates provide insight into potential future climates.
>
> - A relationship exists between the timing of long-term past climate change (i.e., glacial and interglacial cycles) and the timing of changes in certain earth-orbital parameters. This relation establishes a millennial-scale climate-change clock that provides a means to predict the timing of future climate changes.
>
> - A relationship exists between the characteristics of past climates and the sequence of those climates in the long, approximately 400,000-year, earth-orbital cycle. The characteristics of past glacial and interglacial climates within the long earth-orbital cycle differ from each other and do so in a systematic way. This climate-sequence relationship provides a defensible criterion for the selection of a particular past climate as an analog for future climate.
>
> - Long-term, earth-based climate forcing functions, primarily tectonics, have remained relatively unchanged during the last 400,000 years and will likely not change during the next 10,000 years. *The potential and practically unpredictable impact of long-term, earth-based forcing functions on climate is not considered for forecasting climate change over the next 400,000 years.*

> *Because direct testing or analysis cannot be used to confirm the first three assumptions, which are interrelated to each other, the validity of a particular past climate as a future-climate analog can be confirmed only through the passage of time (within the 10,000-year period).* The assumption that long-term, earth-based forcing functions will not change during the next 10,000 years is consistent with the U.S. Environmental Protection Agency final rule 40 CFR Part 197 with respect to the stability of geologic processes ….” (emphasis added)

Thus, the approach that has been taken to the problem of estimating very distant future climates at Yucca Mountain assumes that future climates will most probably be a replay of recent past patterns. One set of difficulties lies in interpreting the geological and paleobotanical records in terms of climate, evaluating past patterns and the uncertainties involved in applying past climate data to the future. The other set lies in determining which past time interval is the appropriate analogue—this determination necessarily involves the implicit or explicit evaluation of the relative importance of key forcing factors in Earth’s past climatic change. In other words, either explicitly or implicitly the choice of paleoclimate analogue presumes an underlying model for the relative importance of orbital forcing for example relative to greenhouse gases or land cover changes.

A.4.3 Uncertainties due to Uncertainty in Interpreting Past Records

Climate is very location specific. It depends not just on latitude and elevation, but on nearby topography and bodies of water. Paleobotanical climatic inferences must therefore be based on local studies, and should take into account landscape differences. GCM’s do not yet have sufficient spatial resolution to produce satisfactory results in mountainous terrain. Meteorologically, Yucca Mountain lies in the rain shadow of the Sierra-Nevada mountain range. Consequently, inferences from the geological past must consider that the Sierras have risen during the past few million years. Correspondingly, estimates of future climate must consider possible future landscape changes, which would have to take into account the current tectonic situation in the western US.

An assumption in current assessments of Yucca Mountain is that the differences in temperature and precipitation experienced during the last glacio-pluvial maximum, about 18,000 years ago, compared to modern temperature and precipitation in the mountain ranges in southern Nevada (Spaulding, 1985), apply to future glacial conditions at Yucca Mountain. It is assumed that temperature and precipitation differences between climate conditions are not strongly altitude dependent. In other words, the same temperature difference between full glacial and post glacial in nearby mountain ranges applies to Yucca Mountain. Spaulding’s conclusions are based on comparisons of plant species growing today under certain conditions of temperature and precipitation with altitudes of the same plant species found in radiocarbon-dated packrat middens at lower altitudes. From this and present-day altitudinal effects on temperature and precipitation, he inferred maximum climate change since the last glacial maximum in the southern Nevada area.

The seasonal climate differences for full glacial conditions Spaulding (1985) reported are, with respect to present-day climates:

- Winter temperature: at least 6 K cooler

-	Summer temperature:	7 to 8 K cooler
-	Annual temperature	6 to 7 K cooler
-	Winter precipitation:	60 to 70% wetter
-	Summer precipitation	40 to 50% drier
-	Annual precipitation	30 to 40% wetter

Note that these conditions apply to maximum glacio-pluvial climate conditions. Stable isotope trends in ice-cores and marine microfauna indicate that the Earth spent only a fraction of the Glacial Era in the full glacial mode.

DOE divided the climate states for the next 10^4 years into three climate states (BSC, 2004):

> “Three potential climate states (interglacial, monsoon, and glacial transition) are forecast for the next 10,000 years based on the examination of past proxy climate records, including ostracode and diatom assemblages recovered from the Owens Lake core (USGS 2001a; Sharpe 2003). The interglacial climate state is comparable to the relatively warm present-day climate state. The monsoon climate state is characterized by hot summers with increased summer rainfall relative to the present-day climate. The glacial-transition (or intermediate) climate state has cooler and wetter summers and winters relative to the present-day climate state.”

A.5 NRC Expert Elicitation of Future Climate in the Yucca Mountain Vicinity, DeWispelare, et al. (1993)

The most relevant of expert elicitations regarding future climate at Yucca Mountain was conducted by the Center for Nuclear Waste Regulatory Analyses (DeWispelare et al., 1993). Of approaches to predicting climate up to a million years henceforward, this is the most diverse of past elicitations. Rather than presenting a single conceptual model, this report presents future climates from the perspectives of five individual experts. The authors produced a summary of the results, while maintaining the individual judgments and perspectives. This is a valuable approach for several reasons:

- The future holds so much uncertainty and is so complex, and so riddled with knowledge gaps, that expert opinion is often the only way to obtain an estimate of the level of confidence in climate predictions.
- Diversity of opinion clearly displays the areas of uncertainty, and hence the areas where research should focus.
- Conversely, areas where experts agree are areas where there is greater consensus, and less controversy. However, consensus does not mean truth.

The process was structured in a way that constrained the experts to provide specific answers to questions about climate controls for the time frames:

- Present,
- AD 2000 to 2100,

- AD 2100 to 2400,
- AD 2400 to 3000,
- AD 3000 to 5000,
- AD 5000 to 7000,
- AD 7000 to 9500, and
- AD 9500 to 12,000.

For each time frame the participants listed primary climate forcing factors (e.g., greenhouse gases, orbital insolation), global temperature difference from present, and annual and seasonal temperature and precipitation differences from today. They also gave probabilities for extreme precipitation events of 20 years duration. These included events caused by large ENSO (El Niño Southern Oscillation), major volcanism and solar variability.

In addition to displaying expert assessments of several aspects of future climate change (temperature and precipitation in the form of cumulative probabilities) in a series of time frames, DeWispelare, et al. (1993) also contains articles written by the individuals. These are both informative in themselves, and also reveal individual perspectives.

Consideration of Analogues from the 'Deeper' Past

The information in this Appendix shows that climate has changed substantially in Western North America as a whole on all time scales and in all past time intervals. Broadly speaking however, the aridity of the modern West is unusual and not necessarily stable. This observation suggests that the recent past may not be an appropriate reflection of what may happen in the future at Yucca Mountain. This observation, therefore, illustrates the considerable uncertainty about projections of future climate that would be needed for TSPA.

A.6 Future Climate Details Needed to Confidently Model Local Hydrologic Responses

Past climate data are typically in the form of average temperature and precipitation differences compared to present conditions. In some cases seasonal differences are estimated. GCM simulations are available in seasonal or monthly summaries, usually in the form of differences from current climates. These differences are most relevant to a site-specific study because the spatial resolution of the current generation of GCM's limits their ability to model exact temperatures and precipitation amounts for specified local conditions.

Although seasonal averages for temperature are somewhat useful in understanding the general climate character of the site, seasonal average values for precipitation are of little value in modeling net infiltration. This is apparent from the fact that infiltration depends strongly on the pattern of precipitation, especially in arid and semiarid climates in which the potential evaporation exceeds, sometimes greatly exceeds, the precipitation. In places where potential evaporation exceeds precipitation, as is the case for Yucca Mountain now, net infiltration occurs only if precipitation events are extended in time, or sufficiently closely spaced to allow water to seep down deep enough to continue downward without complete evapotranspiration. Only event-based (stochastic) precipitation models are applicable to infiltration simulation under such conditions.

DOE summarizes the work it has done on converting future climate states into net infiltration as follows (BSC, 2004):

> Intensive surface-based investigations at Yucca Mountain started in the early 1980s (Wang and Bodvarsson 2003), which have resulted in a number of conceptual models of infiltration (Flint, A.L. et al. 2001) and infiltration predictions for the present-day and future climates, using time-series data from a number of climate analog sites (Flint, A.L. et al. 2001; Hevesi et al. 2003). To represent the large-scale (volume-averaged) Yucca Mountain infiltration processes, the conceptual and numerical models of infiltration involve a number of simplifications (the validity of these simplifications is discussed in Section 4.2), such as:
>
> - Describing infiltration using the water balance (bucket-type) model for one-dimensional piston-like flow
>
> - Neglecting nonlinear effects in partially saturated soils and fractured rock, lateral flow at the soil–rock interface, preferential flow through heterogeneous soils and fractures, flow under conditions where the soil moisture content is below the field capacity, and redistribution of water caused by fracture–matrix interaction
>
> - Using empirical relationships for saturated and unsaturated hydraulic conductivity and water retention, evapotranspiration, surface runoff, and surface run-on."

Another Yucca Mountain model translating climate states into net infiltration was presented in EPRI (1996). This model has a precipitation model capable of simulating different storm types, and the integration of Markov chains into the recurrence probabilities of winter-type storms. The model's time base is in the form of days of the month. A day may or may not experience precipitation. This allows more straightforward calibration with standard reports of meteorological data, and verification with independent datasets. Model parameters are adjusted to match precipitation during the various climate modes identified for future climates expected for Yucca Mountain. Not included in this model is the probability of extreme, very rare events, which may not appear in meteorological records, but are recorded in the geological record (see Baker, 1994; Kleme, 1993, Enzel, et al., 1993, Mares and Mares, 1993).

Craig and Murphy (1989) estimated the probabilities of future climates for the next 10,000 years based on a statistical analysis of climates during the Quaternary Period. Dickinson, et al. (1989) generated a community climate model (CCM) nested within a GCM to simulate precipitation at Yucca Mountain. Simulated modern precipitation for the CCM is in better agreement with measured values than those from the GCM. Their model yielded present-day infiltration rates up to 0.02 mm/day, which is about 7.3 mm/year. This is almost twice the value assumed by Sinnock, et al. (1987), and over an order of magnitude greater than the 0.5 mm/yr value of Montazer and Wilson (1985). The calculations of Dickinson et al. (1989) do not extend to future climates. This first-principles approach shows promise for improvement in simulations of present and future climates.

Event-based stochastic models are appropriate for input to infiltration or flood-frequency simulations because they more closely emulate natural processes than do values for average seasonal or monthly precipitation. This is especially important in cases of arid and semi-arid climates in which the potential evaporation exceeds annual precipitation. In these cases, if precipitation were evenly distributed throughout the year, season or month, no infiltration or flooding would occur. It is the clustering of precipitation events that enables infiltration. Thus, hypothetically, at a particular site, with a given average annual rainfall, a wide range of infiltration amounts is possible, depending on the time distribution of precipitation. For this reason, the stochastic model must, inasmuch as possible, mimic natural rainfall distributions. This is a problem for future climate states for which rainfall distribution data is nonexistent.

Most continental temperate zones have complex meteorology. The Yucca Mountain vicinity is no exception. Hevesi, et al. (1996) have identified 5 distinct storm types that contribute precipitation to Yucca Mountain. Each of these types can have distinctive properties in terms of recurrence intervals, persistence characteristics, mean rainfall amount per day, and season of occurrence. Thus, the model should contain a selected mixture of mathematical functions to simulate the various storm types in the appropriate seasons. A model must also be able to produce the year-to-year variability found in nature.

A.7 Long-Term Uncertainties in Climate/Net Infiltration

DOE noted the timing of climate change over the next 10,000 years is uncertain due to uncertainties in:

> "…the determination of age from the Devils Hole records, caused by ambiguity in selecting a precession value that marks the Devils Hole δ^{18}O inflection points; and the effect of a regional climate on the Devils Hole signal itself, if a primary inflection point precedes or follows a global change. This uncertainty relates, in general, to the issue of correspondence between the orbitally tuned and the terrestrial-based (Devils Hole) records …, as well as Owens Lake chronology, based on the ostracode and diatom data…." (BSC, 2004)

and

> "Uncertainty in the methodology of climate analysis arises from several reasons. It arises from the hypothesis of using the past cyclic climate behavior to forecast the future climate states …; however, the validity of this hypothesis about the climate cycling pattern can be confirmed only by the passage of time …. Uncertainty arises from the possibility for earth's orbital parameters to correlate with other factors that cause climate changes (e.g., solar output or other mechanisms) …. The use of a conventional numerical method, including a correlation analysis, is restricted, because even modern science does not know with certainty all reasons for climate changes, so that the change in a climate system cannot be described numerically and long-term time series cannot be constructed (climate change is time-transgressive and climate proxies do not often record climate events in the same manner or with the same magnitude), nor is there a clear knowledge about future boundary conditions needed for numerical modeling; consequently, the climate analysis is based on forecasting future climate …." (BSC, 2004)

and

> "Uncertainty also arises from the well-known fact of the chaotic nature of the climate system …. The chaotic behavior is caused by a combined effect of several nonlinear dynamic processes, along with positive and negative feedback mechanisms; for example, input of cosmic material (meteorites), changes in solar radiation, ocean salinity, land features (e.g., topography, vegetation, albedo), and atmospheric composition (e.g., fossil fuel emissions, volcanic eruptions). For such a system, precise predictions of long-term climate changes are limited, while the range of long-term changes can be evaluated using stochastic methods, with the aid of probability distributions for such meteorological parameters as precipitation and temperature." (BSC, 2004)

DOE notes, however, that uncertainty in the timing of the change from one climate state to another was dealt with to some extent by selecting steady-state hydrologic responses to a very limited number of climate states (just three during the first 10,000 years). DOE also noted that conservative net infiltration assumptions were made, which they argue is consistent with NRC guidance (BSC, 2004).

Recently, the US Geological Survey (USGS) has developed an increasingly sophisticated basis for evaluating past variability in infiltration rate by examining the growth rates of calcite and opal in the Exploratory Studies Facility Tunnel (USGS, 2001; Paces et al., 2002; Marshall et al., 2003). These data suggest that the deep environment is buffered from dramatic changes in infiltration rates, even over time scales during which major pluvial events have occurred. DOE is taking increasing note of these data, and they may form part of the technical basis for infiltration in the future (Andrews, 2005). At this stage, it is simply useful to note that there remains uncertainty in the linkage between climate and net infiltration at Yucca Mountain, and that past evaluations of the infiltration may have overstated the variability of infiltration in time. This is yet another example of the uncertainties associated with projecting system performance into periods in which pluvial conditions may exist.

A.8 Very Long-Term Climate/Human Behavior Issues

Major climatic changes, notably well-accepted glacial cycles, will occur over tens of thousands of years and affect all regions (hence, all potential repository sites) of the world. It should be noted that repositories in different parts of the world would be affected in different ways by the onset of global glaciation. In particular, repositories at high latitudes (e.g., Finland) would need to consider the onset of global glaciation differently than would Yucca Mountain. Therefore, lessons from international programs must be applied with caution to Yucca Mountain. Human behavior rapidly evolves in response to such changes in climate-induced changes to the biosphere, as well as to other social and cultural factors that cannot be predicted *in their details* beyond tens of years. However, there is no indication that human activities in the future will stray from the broad categories represented by a mixed industrial and agricultural civilization.

Over time periods greater than 10,000 years, however, significant changes in the human species itself are possible. Looking into the past, the period 11,000 to 1.8 million years ago is known as the Pliestocene. The Pleistocene biosphere was close to modern ones: many genera and even species of Pleistocene conifers, mosses, flowering plants, insects, mollusks, birds, mammals, and others survive to this day. Yet the Pleistocene was also characterized by the presence of distinctive large land mammals and birds. Mammoths and their cousins the mastodons, long horned bison, sabre-toothed cats, giant ground sloths, and many other large mammals characterized Pleistocene habitats in North America, Asia, and Europe. Native horses and camels galloped across the plains of North America. Great teratorn birds with 25-foot wingspans stalked prey. Around the end of the Pleistocene, all these creatures went extinct (http://www.ucmp.berkeley.edu/quaternary/ple.html).

Homo erectus emerged 1.6 million years ago and used fire by 1 million years ago. Homo neanderthalensis emerged by 300,000 years ago. The Pleistocene also saw the evolution and expansion of our own species. Homo sapiens first began to appear 120,000-100,000 years ago and by the close of the Pleistocene, humans had spread through most of the world (http://anthro.palomar.edu/homo2/modern_humans.htm). The time scales being considered for compliance assessment are therefore seen to be comparable to time scales for evolution of hominid species.

EPA also acknowledged these difficulties in their support for the 40 CFR 197 rulemaking (66 FR 32099):

> "… beyond 10,000 years it may be possible to make general predictions about geological conditions; however, the range of possible biospheric conditions and human behavior is too wide to allow ''reliable modeling'' ... It is necessary to make certain assumptions regarding the biosphere, even for the 10,000-year alternative, because 10,000 years represents a very long compliance period for current-day assessments to project performance. For example, it is twice as long as recorded human history… For periods approaching the 1,000,000 years that NAS contemplated under the peak dose alternative, even human evolutionary changes become possible."

A.9 Summary and Conclusions

All scientific predictions are based on observations of past phenomena with educated estimates of future trends in technology, populations and societal responses. If understanding of these phenomena is based on well-known physical laws, gravity and planetary motion, for example, and uncomplicated by other interferences, such as a rogue comet, predictions can have a high degree of accuracy. If, on the other hand, the forces governing the phenomena of interest are affected by several forces, some of which involve elements of statistical probability, predictions become less deterministic. Daily weather forecasts are an example. On a much longer time scale, future climate change is indeterminate. This is, in part, because many causal elements are uncertain. Moreover, there is no exact historical or geological analog to future climate. The positions of the continents, and ocean and atmospheric circulation patterns change over long time periods. Climatology is not a controlled experiment that can be exactly replicated. Consequently, long-term climate predictions necessarily have a measure of uncertainty. These predictions are given estimated probabilities, based on current understanding of the controlling forces and uncertainties.

One of the key parameters that is widely thought to have controlled climate change on both long time scales and short is the atmospheric concentrations of greenhouse gases. Currently, it appears likely that a necessary (but not sufficient) condition for the occurrence of the Quaternary Ice Ages is the crossing of a greenhouse gas threshold equivalent to ~520-1120ppm

CO_2, permitting significant polar ice (in both glacials and interglacials). The greenhouse gas ‘control parameter’ is the one that humans are currently conducting a natural experiment on, pushing values of greenhouse gas concentrations above this threshold. There is no firm basis to assume that glacial-interglacial cycles will continue unimpeded, although this is the explicit assumption upon which all of the future climates used in Yucca Mountain studies are currently based. It is possible that on time scales $>10^4$ years, Earth may emerge from the Ice House state it has been in for the past 5 million years because of greenhouse induced global warming, becoming like the Eocene. It is also possible that this warming will be short-lived or not potent enough to overcome the long-standing orbitally induced glacial-interglacial cyclicity and climate will continue along as it has in the Quaternary. Or it possible that there is an intermediate range in which glacial-interglacial oscillations increase in magnitude, from a essentially ice-free state to a glacial state as appears to have happened during periods in the Oligocene and Miocene. In short, there is currently significant uncertainty in projections of future global climate over time scales of concern for TSPA. Selection among these projections cannot be done with confidence given current scientific understanding.

In addition to this fundamental, unresolved uncertainty regarding the sensitivity of the modern world to greenhouse gas increase, the fact that this perturbation is entirely a product of human activity and will likely evolve as a product of human behaviors and design in the future cannot be ignored. To assume fixed human behaviors is essentially to accept as the only climate scenario under consideration the most radical of the climate scenarios under consideration by IPCC, i.e., the extension of ‘Business As Usual’-type greenhouse gas emissions for 1,000,000 years. Aside from the fact that this is not a credible extrapolation, it has important implications for which of the climate scenarios discussed above being most likely. Such a large and sustained greenhouse gas release would certainly raise global temperatures past the point where polar ice is untenable. Thus it is logically inconsistent to assume unchanged human behavior and a Quaternary-based regular glacial-interglacial climate scenario—the two are incompatible on long time scales.

Also, as discussed in this Appendix, the response of the Yucca Mountain region to these potential changes in global climate is also uncertain, since the fundamental driving mechanisms for climate in the western US are incompletely understood. Greenhouse gas warming of the earth as a whole could lead to either increases or decreases in precipitation at Yucca Mountain. Furthermore, the link between precipitation and net infiltration at Yucca Mountain remains uncertain, albeit boundable. Finally, all of these factors associated with climate at Yucca Mountain are strongly influenced by human activities, in the Yucca Mountain region and worldwide. Similarly, human activities at Yucca Mountain are influenced by climate state at any time in the future. Selection of a climate projection is therefore unknown to the same extent, and in a similar manner, to human behavior. Following the recommendations of TYMS (1995), therefore, it is necessary to establish stylized bounds for climate in regulatory rulemaking, in the same way that human behavior is stylized as recommended by TYMS (1995).

A.10 References

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