ISSUE RESOLUTION STATUS REPORT ON METHODS TO EVALUATE CLIMATE CHANGE AND ASSOCIATED EFFECTS AT YUCCA MOUNTAIN

(KEY TECHNICAL ISSUE: UNSATURATED AND SATURATED FLOW UNDER ISOTHERMAL CONDITIONS)

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1.0 INTRODUCTION

One of the primary objectives of the Nuclear Regulatory Commission's (NRC's) refocused prelicensing program is to focus all its activities on resolving the 10 key technical issues (KTIs) it considers to be most important to repository performance. This approach is summarized in Chapter 1 of the staff's annual progress reports (e.g., NUREG/CR-6513, Center for Nuclear Waste Regulatory Analyses, 1996). Other chapters address each of the 10 KTIs by describing the scope of the issue and subissues, path to resolution, and progress achieved during fiscal year (FY) 1996.

Consistent with 10 CFR Part 60 requirements and a 1992 agreement with DOE, staff-level issue resolution can be achieved during the prelicensing consultation period; however, such resolution at the staff level would not preclude the issue being raised and considered during the licensing proceedings. Issue resolution at the staff level during prelicensing is achieved when the staff has no further questions or comments (i.e., open items) at a point in time, regarding how the DOE program is addressing an issue. There may be some cases where resolution at the staff level may be limited to documenting a common understanding regarding differences in the NRC and the DOE points of view. Pertinent additional information could raise new questions or comments regarding a previously resolved issue.

An important step in the staff's approach to issue resolution is to provide DOE with feedback regarding issue resolution, before the viability assessment. Issue Resolution Status Reports (IRSRs) are the primary mechanism that the staff will use to provide DOE feedback on the subissues making up the KTIs. IRSRs comprise 1) acceptance criteria which will be used by the staff to review the DOE license application and prelicensing submittals, as well as indicating the basis for resolution of the subissue, and 2) the status of resolution including where the staff currently has no comments or questions as well as where it does. Feedback is also contained in the staff's annual progress report, which summarizes the significant technical work toward resolution of all KTIs during the preceding FY. Finally, open meetings and technical exchanges with DOE provide opportunities to discuss issue resolution, identify areas of agreement and disagreement, and develop plans to resolve such disagreements.

In addition to providing feedback, the IRSRs will be guidance for the staff's review of information in DOE's viability assessment. The staff also plans to use the IRSRs in the future to develop the Standard Review Plan (SRP) for the repository license application.

Each IRSR contains five sections, including this introduction in Section 1.0. Section 2.0 defines the KTI, all the related subissues, and the scope of the particular subissue that is the subject of the IRSR. Section 3.0 discusses the importance of the subissue to repository performance, including: 1) qualitative descriptions, 2) reference to a total system performance flowdown diagram, 3) results of available sensitivity analyses, and 4) relationship to DOE's Waste Containment and Isolation Strategy (i.e., the approach to its safety case). Section 4.0 provides the staff's review methods and acceptance criteria that will be used to evaluate DOE's prelicensing and licensing submittals. These acceptance criteria are guidance for the staff and indirectly for DOE as well. The staff's technical basis for its acceptance criteria will also be included to further document the rationale for the staff's decisions. Section 5.0 concludes the report with the status of resolution indicating those items resolved at the staff level or those items remaining open. These open items will be tracked by the staff and resolution will be documented in future IRSRs.

2.0 ISSUE/SUBISSUE STATEMENT

This IRSR addresses two subissues of the KTI on Unsaturated and Saturated Flow under Isothermal conditions. The primary objective of this KTI is to assess all aspects of the ambient hydrogeologic regime of Yucca Mountain (YM) that have the potential to compromise the performance of the proposed repository. The secondary objective of this KTI is to develop review procedures and to conduct technical investigations to assess the adequacy of DOE's characterization of key site- and regional-scale hydrogeologic processes and features that may adversely affect performance. Subissues deemed important to the resolution of this KTI have been identified, and are framed as questions:

(i) What is the likely range of future climates at YM?

(ii) What are the likely hydrologic effects of climate change?

(iii) What is the estimated amount and what is the spatial distribution of present-day shallow groundwater infiltration?

(iv) What is the estimated amount and what is the spatial distribution of present-day groundwater percolation through the proposed repository horizon?

(v) What is the estimated amount and what is the spatial distribution of groundwater percolation through the proposed repository horizon during the period of repository performance?

(vi) What are the ambient flow conditions in the saturated zone?

This IRSR addresses subissues (i) and (ii) above. It focuses on methods for estimating future climate change at YM and its associated hydrologic effects. Climate itself is defined by the prevailing meteorological conditions, including temperature, precipitation, and wind. These factors, along with local geologic conditions and plant communities, control the rates of infiltration, deep percolation, and groundwater seepage through a geologic repository located in an unsaturated environment.

This report summarizes the pertinent conclusions of numerous climate-related publications that are relevant to YM. Based on the extensive scientific literature, the NRC staff concludes that reasonable methods exist to bound the range of future climate change and the resulting consequences. Enough information is currently available to reasonably estimate the range of future climates and water-table rise at YM. A procedure and acceptance criteria are provided for reviewing DOE's evaluations of climate change and related topics, and how they will be used to assess the performance of a high-level waste (HLW) repository.

3.0 IMPORTANCE OF SUBISSUES TO REPOSITORY PERFORMANCE

The Earth's climate could change significantly during the time that nuclear wastes will remain hazardous. Climate controls the range of precipitation, which, in part, controls the rates of infiltration, deep percolation, and groundwater flux through a geologic repository located in an unsaturated environment. Changes in groundwater recharge will likely induce other changes, such as regional fluctuations in the elevation of the water table. Water-table rise would reduce the thickness

of the unsaturated zone barrier. Therefore, future changes in climate could significantly influence the ability of a repository to isolate waste.

The importance of groundwater flux as the key parameter for repository performance in an unsaturated zone is well known, and has been further emphasized by DOE's most recent report (DOE, 1995) on total system performance assessment (TSPA). On page ES-30 of that report it is stated that "...in the overall TSPA analyses, an over-arching theme comes back again and again as being the driving factor impacting the predicted results. Simply stated, it is the amount of water present in the natural and engineered systems and the magnitude of aqueous flux through these systems that controls the overall predicted performance.... Therefore, information on...[this topic]...remains the key need to enhance the representativeness of future iterations of TSPA." Sensitivity studies clearly showed the predominance of percolation flux in estimating cumulative radionuclide releases and peak radiation doses over a 10-kyr (1 kyr=1000 years) period (see DOE, 1995, pp. 10-6 and 10-7).

DOE's "Waste Containment and Isolation Strategy" (DOE, 1996, p. 5) likewise states that "performance assessments have shown that seepage into the emplacement drifts is the most important determinant of the ability of the site to contain and isolate waste." The importance of infiltration as a hydrologic parameter was recognized by the staff in its Iterative Performance Assessment Phase 2. NRC (1995, p. 10-4) states that "Although the flux of liquid water through the repository depends on...infiltration, hydraulic conductivity, and porosity, performance correlates most strongly to infiltration." Finally, Figure 1 (CNWRA, 1994) shows that climate-related matters have been important factors in recent performance assessments.

Water flow through a geologic repository and its environs depends on both surface processes (precipitation, evapotranspiration, overland flow, and infiltration) and subsurface processes (deep percolation, moisture recirculation, and lateral flow). To evaluate the significance of climate change to repository performance, bounds can be determined for either: (i) climate change (and by inference the importance of surface processes), or (ii) the subsurface processes such as shallow infiltration and deep percolation based on geohydrologic parameters, or (iii) both. Obtaining bounds of water flow from both the climate change and from geohydrologic parameters will most likely provide reasonable assurance that water flow has been appropriately incorporated within the TSPA for the repository.

At YM, cooler and wetter conditions would increase infiltration and could also significantly affect future human populations in the region, leading to changes in patterns of groundwater and land use. These changes should be considered to a reasonable extent in estimating future doses to the critical group identified for the repository.

The staff is developing a strategy for assessing the performance of a proposed repository at YM. As currently visualized by the staff, key elements of this strategy are defined by those elements necessary to demonstrate repository performance. These elements are illustrated in draft figure A-1 in Appendix A. Acceptance criteria for abstracting each of these elements into a demonstration of compliance are under development. Climate change, as defined by long-term changes in temperature and precipitation, is an important factor in repository performance because it can alter groundwater infiltration, deep percolation, near-field hydrology, and far-field dilution and transport rates. Climate is also a factor in assumptions about the characteristics of a critical group and reference biosphere. Therefore, the acceptance criteria for the treatment of climate are subsidiary to and designed to complement the broader-level acceptance criteria for the abstraction of the key elements.

For DOE to adequately demonstrate and quantify in its TSPA the effects that climate change might have on repository performance, it must consider how these effects interplay with the other factors within and between key elements in the engineered and natural subsystems of the repository. As highlighted in Figure A-1, climate change and its effects are important factors that need to be abstracted into four of the key elements of the engineered and natural subsystems: (1) Quantity and Chemistry of Water Contacting Waste Forms (includes consideration of deep percolation); (2) Spatial Distribution of Flow (includes consideration of infiltration); (3) Volumetric Flow in Production Zones (includes dilution and transport rates); and (4) Location and Lifestyle of Critical Group (includes consideration of water-table rise).

4.0 REVIEW METHODS AND ACCEPTANCE CRITERIA

The NRC staff has determined that methods based on paleohydrologic, paleoclimatic, and geochemical information can be used to gain an adequate understanding of the range of past climates in the YM region. These insights can then be used to estimate the range of future climate variability, information that is needed to conduct meaningful performance assessments for a potential repository at YM. Multiple sources of data are needed to help reconstruct past environmental conditions. These include information from: paleodischarge sites; packrat (*Neotoma*) middens; pollen studies; paleolake levels and sediments; groundwater isotopic data; soil properties; tree rings; erosion studies; and other sources.

Paleoclimatic and paleohydrologic data can serve as "windows" to the past. They can provide "snapshots" of climatic conditions at various time intervals. To provide meaningful results, data sources must provide paleoclimate and paleoenvironmental indicators, along with materials that can be dated with radioisotopes or fossils.

Some data sources are relatively continuous and represent averaged or regional conditions. Ice cores from Greenland and Antarctica have been used to reconstruct high-latitude climate conditions over tens to hundreds of thousands of years. An example from the Great Basin is the 500-kyr temperature proxy record from Devils Hole, which is now recognized as one of the longest and best paleorecords on Earth. This record can be used to directly compare ancient climates of the Great Basin to proxy records from around the world. The Devils Hole site shows how aquifers can serve as "archives" of ancient climatic conditions.

Tree rings provide a relatively continuous record over a shorter time interval, ranging from decades to as much as several millennia for long-lived species. Some paleo data are discontinuous and representative of highly localized conditions. For example, ancient packrat middens preserve plant remains and pollens that can be used to identify local paleo-assemblages of plants. The limited foraging radius of < 50 m (< 164 ft) of modern packrats requires that plant fragments found in ancient middens came from the immediate vicinity. Numerous ancient middens have been found throughout the Great Basin, including a number near YM.

Paleodischarge sites, like the Lathrop Wells Diatomites near YM, are especially powerful sources of information. If they can be dated and verified as having been produced by discharge from the regional water table, then they can establish times of increased groundwater recharge. The data can be used to help understand the response of the hydrologic system to the range of late Pleistocene

	Climate Change
U.S. Nuclear Regulatory Commission, Phase 1 (NRC, 1992)	• Increased Infiltration • Water-Table Rise
U.S. Nuclear Regulatory Commission, Phase 2 (NRC, 1995)	• Increased Infiltration • Water-Table Rise
Sandia National Laboratories, TSPA 1991 (SNL, 1992)	• Increased Infiltration
Pacific Northwest Laboratory (PNL, 1993)	• Increased Infiltration
Electric Power Research Institute, Phase 1 (EPRI, 1990)	• Increased Infiltration
Electric Power Research Institute, Phase 2 (EPRI, 1992)	• Increased Infiltration - Current - Greenhouse - Micropluvials • Water-Table Rise

Figure 1. Comparison of implementations of climate scenarios for Yucca Mountain. (after CNWRA, 1994, p. 7-4)

climatic conditions. The past extent of pluvial lakes in the Great Basin also reflects enhanced recharge conditions on a regional scale.

The staff's technical review of DOE's treatment of future climate will be based on professional judgments regarding the completeness and applicability of the data and evaluations presented by DOE. It is expected that DOE will summarize or document the results of all significant paleo-studies that have been conducted in the YM region. The staff will determine whether DOE has reasonably complied with the Acceptance Criteria in sections 4.1 and 4.2 below.

4.1 Climate Change

It will be necessary for DOE to develop assumptions about future climate change at YM. Staff will review DOE's assumptions to determine whether they are consistent with known trends of past climatic variation. The following *Acceptance Criteria* apply:

- Climate projections based primarily on paleoclimate data are acceptable for use in performance assessments of the YM site. During its review, the staff should determine whether DOE has made a reasonably complete search of paleoclimate data that are available for the YM site and region, and has satisfactorily documented the results. Staff should determine that, at a minimum, DOE has considered information contained in Forester, et al. (1996); Winograd, et al. (1992); Szabo, et al. (1994); and other reports that may become available.

- DOE's projections of long-term climate change are acceptable if these projected changes are consistent with evidence from the paleoclimate data. Specifically, staff should determine whether DOE has evaluated long-term climate change based on known patterns of climatic cycles during the Quaternary, especially the last 500 kyr. The current analysis indicates that these cycles included roughly 100-kyr cycles of glacial/interglacial climates, with interglacials lasting about 20 kyr. Current information also suggests that past climate conditions were cooler and wetter than today, about 60 to 80 percent of the time.

- The staff will not require climate modeling to estimate the range of future climates. If DOE uses numerical climate models, determine whether such models were calibrated with paleoclimate data before they were used for projection of future climate, and that their use suitably simulates the historical record.

- Values for climatic parameters (time(s) of onset of climate change; mean annual precipitation (MAP); mean annual temperature (MAT); etc.) to be used in DOE's safety case must be adequately justified. Determine whether appropriate scientific data were used, reasonably interpreted, and appropriately synthesized into parameters such as MAP, MAT, and long-term climate variability. The current knowledge about these parameters, coupled with past climate change, will require that, as a bounding condition, a return to full pluvial climate (higher precipitation and lower temperatures) be considered for at least a part of the 10-kyr period (current information does not support persistence of present-day climate for a duration of 10 kyr or more). The current interpretations of paleoclimate data indicate an increase in MAP by a factor of 2 to 3 and a lowering of MAT of 5-10 °C (9-18 °F) during the pluvial climate episodes.

- If DOE uses expert elicitation to arrive at values of climate parameters, determine whether the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996a) was followed by DOE.

4.1.1 Technical Bases for Review Procedures and Acceptance Criteria (Climate Change)

- Overview of Climate Change

Climate change is one of the most important factors that can influence the isolation of HLW in a geologic repository. Therefore, it is necessary for DOE to estimate the range of future climatic conditions to provide inputs to performance assessments. The study of climate change seems a formidable task because it involves both natural and anthropogenic components. Long-term natural variations in climate are clearly seen in the paleoclimatic record of the last 500 kyr. Five glacial/interglacial cycles occurred during that interval, each lasting roughly 100 kyr.

Climate has been changing since the world began, billions of years ago. Earth's early atmosphere was probably dominated by carbon dioxide (CO_2), and it took billions of years for algae in the world's oceans to remove most of that gas and replace it with enough oxygen to sustain life on the continents. The sheer mass of carbonate sedimentary rocks on Earth shows the effectiveness with which biological and chemical mechanisms have gradually removed carbon from the atmosphere (see Krauskopf, 1967, Table 21-2).

The causes of climate change are receiving close scrutiny from the scientific community. Natural variations in the Earth's orbital parameters (Milankovitch hypothesis) must play a significant role. But exactly how long-term climate shifts occur is unclear because complex, non-linear, feedback mechanisms probably exist within the atmosphere-hydrosphere-cryosphere system. Plate tectonics also plays a role by controlling the distribution of land masses and major topographic features.

Human influences on the climate are very recent, providing no long-term history of human influences that could help to project future anthropogenic changes or the manner in which natural cycles may be altered. Only unreliable speculation is available to predict the manner and degree to which future human activities would affect climate over many thousands of years. Human activities could, under various circumstances, delay or even advance a transition to the next glacial stage. But there is general agreement that the chief concern is the addition of greenhouse gases to the atmosphere caused by combustion of fossil fuels. The average temperature at the Earth's surface is thought to have risen by about 0.5 °C (0.9 °F) in the last century, and sea level along the U.S. coast is estimated to be rising 2.5-3.0 mm/yr (0.10-0.12 in/yr). But these changes cannot yet unambiguously be labeled as results of greenhouse warming. One reason for this is that recent ice core data have revealed natural oscillations in climate on a scale of 10-100 years. Also, during the last interglacial (circa 125 kyr ago), sea level stood for a time about 6 m (20 ft) above the present level. This was caused by natural variation because there were no significant human influences on climate at that time.

Substantial reserves of fossil fuels still exist on Earth, but most of the remaining resources will probably be depleted on a time scale of centuries rather than millennia. The question then remains. How long will the legacy of an enhanced greenhouse effect continue after fossil fuels are gone? The answer to this question is uncertain, although it is possible that centuries will pass before excess CO_2 concentrations in the atmosphere could return to pre-industrial levels. The complex oceanic and terrestrial mechanisms that remove carbon from the atmosphere continue to be the foci of extensive

research. General circulation models have been applied to these problems, but the data required to greatly improve general circulation modeling are not yet available. General circulation models themselves have limitations, as do all numerical models.

It has been argued that the next 200 years of anthropogenic climate change may create conditions unprecedented in human history. There are predictions of drought-induced famines, the spread of tropical diseases, coastal flooding from sea-level rise, a dramatic increase in the numbers and intensities of hurricanes, and even "run-away" greenhouse effects with drastic biological consequences. The scientific literature includes examples of heated debate about the rate of atmospheric change and the national and international actions that should be taken. Recent assessments of climate change have scaled back the estimated rate of greenhouse warming, one reason being that oceanic and terrestrial carbon sinks may be more effective than previously thought. The climate is still susceptible to so-called "abrupt transitions," which have occurred naturally on time scales of decades or less even during the Holocene. Chaotic changes in ocean currents may be partly responsible for this. Fortunately, on a global scale there is a built-in resistance to drastic climate change, mainly because of the enormous heat capacity of the hydrosphere. This fact is undoubtedly responsible for the long-term evolution and abundance of life on Earth. The complex interactions between the atmosphere, cryosphere, and the hydrosphere provide mechanisms that help to buffer global climate shifts.

Given the realities outlined above, and the need to proceed with reasonable performance assessments, the staff recommends a pragmatic approach to address climate change and its effects. The staff has determined that anthropogenic changes to the atmosphere are detectible and likely to increase with time. The effects of global, enhanced, greenhouse warming will be presumed to last no more than several thousand years, and that, about 3 kyr in the future, the climate at YM will resume or continue the global cooling predicted by the Milankovitch orbital theory of climate. Staff will postulate that full pluvial (cooler and wetter) conditions will dominate at least several thousand years of the next 10 kyr. In other words, anthropogenic effects will be assumed to delay but not prevent an inevitable return to pluvial conditions at YM. Pluvial conditions of higher effective moisture would be reasonably challenging to repository performance, providing conservatism for NRC's safety analysis.

- Natural Variations in Climate

Lamb (1972, 1977) provides a detailed overview of the many mechanisms and phenomena that contribute to climate variability and change. The present-day global climate is part of a sequence that began about 2 million years ago, the beginning of the Quaternary Period. The Quaternary itself is divided into the Pleistocene and Holocene epochs. The Holocene began about 10 kyr B.P. The Quaternary differs climatically from the earlier, generally warmer Tertiary Period because the glaciations were more severe and extensive than those of the late Tertiary. The Tertiary and Quaternary periods comprise the Cenozoic era. The Pleistocene glacial/interglacial cycles were most pronounced in the past million years, during which ten cycles are thought to have occurred. The best long-term records of this climate variability are provided by ice cores, cores from vein calcites, and samples from deep ocean sediments (Dansgaard, et al., 1993; Winograd, et al., 1992; Lamb, 1977).

The reasons for the climate cooling of the late Cenozoic are unknown, but an interesting hypothesis involves plate tectonics. Raymo and Ruddiman (1992, p. 119) propose that

> ...late Cenozoic uplift of the Himalayan region and Tibetan plateau would have resulted in regionally, and hence globally, higher chemical erosion rates, causing a drawdown of atmospheric CO_2 and global cooling. The timing of this tectonically driven CO_2 decrease should be post-Eocene, coincident with the formation of the Tibetan plateau and in agreement with geological evidence for when global cooling was most rapid.

If this tectonic uplift hypothesis is ever verified, it would demonstrate the sensitivity of global climates to relatively small changes in atmospheric composition. Other events that may have helped lead to cooler climates include the occupation of the south polar region by Antarctica and creation of a nearly enclosed Arctic Ocean fringed by mountainous lands (Lamb, 1972, p. 38). However, Raymo and Ruddiman (1992) state that these events cannot account for the observed magnitude of Cenozoic global cooling.

It seems likely that more than one mechanism must be responsible for the Tertiary/Quaternary climate shift. Broecker (1997) points out that water vapor is in fact the principal greenhouse gas in the Earth's atmosphere. He speculates that climate shifts could be caused by changes in the water-vapor budget for the atmosphere, perhaps caused by chaotic changes in global ocean currents, which play a major role in the transfer of heat from the tropics to the poles (Broecker, 1995 and 1997). The potential for climate to be influenced by changes in the energy output of the sun was investigated by Wigley and Raper (1990). They used solar irradiance reconstructions back to 1874 to estimate the effects on global-mean temperatures. Modeled temperature changes were shown to be relatively insensitive to model uncertainties. They concluded that the direct effects of irradiance changes on global-mean temperature are likely to be very small. However, given limitations of available data, the question of low-frequency solar effects on climate remains open (Wigley and Raper, 1990, p. 2171) and can only be addressed by decades of additional data collection. More recent work suggests that low-frequency solar effects are reflected in global temperatures (Lean and Rind, 1994; Kerr, 1996).

The astronomical theory of Milankovitch is a widely accepted model for the stimulus of long-term, natural climate change. Crowley (1996, p. 5) states that the "...onset and recovery from Ice Age conditions is [are] now attributed to slow changes in the Earth's orbit -- the so-called Milankovitch effect -- that modify the seasonal cycle of solar radiation at the Earth's surface." Lamb (1972, p. 30) compared the Milankovitch effect with the effects of solar variations.

> Much greater variations of the Earth's annual radiation budget must occur through very long-term, periodic changes in the Earth's orbit, the tilt of its rotation axis and the seasonal variation of the Earth's distance from the sun characteristic of epochs defined by the orbital situation. Such epochs commonly change their character only slowly, over some thousands of years. But the changes are big, and some effects on climate appear inescapable, probably including the causation of the alternation of ice ages and warm interglacial periods during the Quaternary era...when the large-scale geography has been much as now.

Changes in insolation caused by precessional variations of the earth's orbit and varying tilt of the Earth's rotation axis (Milankovitch model) are known to correlate to some degree with past variations in global ice volumes. Tilt varies with an average period of 41 kyr and precession with an average period of 21 kyr (Kominz and Pisias, 1979). The periodicity of variations in the eccentricity of the earth's orbit is about 100 kyr. Kominz and Pisias (1979) found that, based on simple linear models, less than 25 percent of the variation in global ice volume during the last 730 kyr is related to tilt and

precession. They concluded that Pleistocene glacial variations are largely stochastic in nature. No evidence was found for a linear relationship between eccentricity and ice volume, but Kominz and Pisias did note the existence of a dominant 100-kyr cycle of climatic change. Although tilt and precession are not strongly correlated to global ice volume, they evidently have the potential to trigger or enhance climatic shifts.

Lamb (1977, p. 312) found that the periodicity seen in paleoclimate data was "...so close to the periods of the Earth's orbital variables as to constitute a remarkable vindication of Milankovitch's ...hypothesis regarding the origin of the Quaternary glacial-interglacial cycles.... It is only curious that the 100,000-year time scale is always more prominent than the theory suggests." Historical proof of the gradually changing tilt of the Earth's axis may be found in the monuments throughout the world that mark former latitudes of the Tropic of Cancer and the Tropic of Capricorn (Chao, 1996). The Tropic of Cancer will continue to move south another 90 km (56 mi) before it reverses in about 9300 years and migrates northward.

In a milestone paper, Hays, et al. (1976, p. 1131) likewise concluded that "...changes in the earth's orbital geometry are the fundamental cause of the succession of Quaternary ice ages." Their conclusion was based on analyses of long-term (> 20 kyr) variations in paleoclimate data compared with predictable orbital and insolation changes. They noted that an explanation of the correlation between the dominant 100-kyr climate cycle and orbital eccentricity probably requires an assumption of nonlinearity. At variance with Hays, et al., Winograd, et al. (1992, p. 259) concluded that the paleoclimate record from the carbonate aquifer at Devils Hole was

> ...inconsistent with the Milankovitch hypothesis that orbitally controlled variations in solar insolation play a direct role in Pleistocene climate change. The hypothesis fails to predict the timing of deglaciations during the period 500 to 100 ka [kyr]. During the middle-to-late Pleistocene the increase in the duration of glacial cycles from about 80,000 to 130,000 years suggests that climate shifts were aperiodic. Interglacial climates lasted on the order of 20,000 years.

Winograd, et al. (1992, p. 258) did note that "Obliquity and precession periodicities are evident in the DH-11 record [based on a 36 cm (14 in) core of vein calcite from Devils Hole]. Such periodicities suggest that although solar insolation may not be the primary determinant of the onset of glacial-interglacial shifts, astronomical geometry could still be one of several factors contributing to Pleistocene paleoclimate changes." An independent confirmation of two samples from the Devils Hole chronology has been provided by Edwards, et al., 1997. They used a dating technique based on protactinium-231 to check both the Devils Hole record and records of sea-level change in Barbados corals. Compared with previous dating methods, the Devils Hole samples yielded consistent dates. Therefore, if the samples are representative, the record is accurate. The Barbados data support the astronomical theory of climate change. Differences found in the Devils Hole record are apparently real, but may represent local climatic events (Edwards, et al., 1997; Kerr, 1997).

Regardless of the actual causes of the Pleistocene climates, four glacial stages have occurred in the last 400 kyr. Forester (1996) considers that a full glacial "mega cycle" lasts about 400 kyr and contains glacial/interglacial subcycles of roughly 100 kyr. Forester believes that the Devils Hole record shows that the southern Nevada climate responds to solar insolation on a millennial time scale.

The present Holocene climate has remained relatively stable, even in view of intervals like the so-called "Little Ice Age" that occurred during the period from about 1450 to 1890 (Crowley, 1996). However, Dansgaard, et al. (1993) raised the question of whether the Holocene will remain stable despite anthropogenic effects. They reported evidence for general instability of past climate based on ratios of stable oxygen isotopes in Greenland ice cores. Their high-resolution data suggest that, except for the Holocene, the North Atlantic region has been relatively unstable during the last 230 kyr. Their conclusions apply even to the two previous interglacial stages.

Following the report by Dansgaard, et al. (1993), the previous interglacial has been studied extensively to gain insights about climate variability during warmer intervals (see *Quaternary Research*, Vol. 43, No. 2, March 1995). The last interglacial (oxygen isotope substage 5e) occurred from about 133 to 114 kyr B.P. (before present), based on Greenland ice core data (Dansgaard, et al., 1993). In North America this interglacial is known as the Sangamon; in Europe it is called the Eemian or Eem. For a time during the Sangamon, sea level stood about 6+ m (20 ft) higher than today (Muhs, et al., 1994; Brigham-Grette and Hopkins, 1995; Neumann and Hearty, 1996). This higher sea level corresponded to a significant reduction in global ice, equivalent to a large percentage of the ice volume in present-day Greenland. There were no significant anthropogenic effects on climate during the Sangamon. It is therefore interesting that a natural sea-level rise occurred that is similar in magnitude to that predicted by some future scenarios of enhanced greenhouse warming. Even higher sea-level rises have occurred in the geologic past. For example, global sea level may have been 25 to 35 m (82 to 115 ft) above present-day sea level during the Pliocene (Cronin and Dowsett, 1993).

- Comments on Anthropogenic Climate Change

Karl, et al. (1997) present an excellent summary of the possible causes and consequences of human-induced climate changes. Because of the complex interactions of the Earth's hydrosphere, atmosphere, and cryosphere, the long-term effects of anthropogenic changes to the atmosphere and to the earth's surface (e.g., increase of greenhouse gases, deforestation, abundance of jet contrails, etc.) are still unclear. They could, under various circumstances, delay or even advance a transition to the next glacial stage. Miller and de Vernal (1992) outline conditions in which increased concentrations of greenhouse gases in the atmosphere might lead to ice-sheet growth and an accompanying drop in sea level. It is even possible that reductions in fossil fuel emissions could cause some global warming because of the rapidity with which sulfate aerosols, which are thought to exert a cooling effect, are removed from the atmosphere (Wigley, 1991).

Many of the current concepts regarding anthropogenic changes to climate are predicated on increasing atmospheric CO_2 caused by the use of fossil fuels and biomass burning. Such practices are likely to change as fossil fuels are consumed. Anthropogenic activities also release other greenhouse gases, such as methane and nitrous oxide. Large supplies of fossil fuels still exist on Earth, but the remaining resources will likely last for centuries rather than millennia. Proven energy reserves do not represent total resources, but do provide the best picture of readily available fossil fuels. Proven commercial energy reserves of coal, oil, and natural gas for the world have been estimated at 34.6 x 10^6 petajoules (3.28 x 10^{19} BTUs) (WRI, 1994). Coal is by far the most abundant fossil fuel, and proven world reserves could sustain current production rates for 209 years (WRI, 1994, Table 9.2). Proven reserves of oil and gas could sustain current production for 45 and 52 years, respectively. Crowley (1996) claims that only about 5 percent of the available fossil fuel reservoir has been

consumed to date, but his estimate may not have considered the recent decline in estimated coal reserves in China (WRI, 1994).

As evidence of global warming, investigators have examined whether subtle, long-term changes exist in the temperature record. A report by the Forum on Global Change Modeling (Barron, 1995) gives consensus conclusions about climate change, and specifically temperature. The report found that average global surface air temperatures are about 0.5 °C (0.9 °F) higher than in the last century. However, the change "...cannot yet be unambiguously ascribed to increased concentrations of greenhouse gases." Based on the assumption that greenhouse gases will increase, the report found that it is very probable that mean precipitation will increase, northern sea ice will decrease, and sea level will rise at an increasing rate. If atmospheric CO_2 doubles, global mean surface temperatures will increase by 1.5 to 4.5 °C (2.7 to 8.1 °F), with 2.5 °C (4.5 °F) considered most likely. Mean surface temperatures are estimated to rise 0.5 to 2 °C (0.9 to 3.6 °F) by 2050. But there is also an estimated 10 percent chance that temperatures will rise by over 4 °C (7 °F) by 2100 (Carlowicz, 1995). Carlowicz noted other research that supports the view that even minor changes in global temperature are amplified in the polar regions.

In addition to temperature change, another key variable in tracking global warming is sea-level rise. Titus and Narayanan (1995) reported that sea level is currently rising 2.5 to 3.0 mm/yr (0.10 to 0.12 in/yr). In a detailed report, they assessed the probability of future sea-level rise. Their study consisted of two phases. In the first phase they developed a simplified model for estimating sea level rise as a function of 35 major uncertainties. The report by Titus and Narayanan (1995, p. 1 of summary)

> develops probability-based projections that can be added to local tide-gauge trends to estimate future sea level at particular locations. It uses the same models employed by previous assessments of sea level rise. The key coefficients in those models are based on subjective probability distributions supplied by a cross section of climatologists, oceanographers, and glaciologists. The experts who assisted this effort were mostly authors of previous assessments by the National Academy of Sciences and the Intergovernmental Panel on Climate Change (IPCC).

In phase two the results were documented in a draft report that was circulated to a panel of experts. Feedback from the experts was then used to revise the analyses. Titus and Narayanan (1995, p. 2 of summary) concluded that "Global warming is most likely to raise sea level 15 cm by the year 2050 and 34 cm by the year 2100. There is also a 10% chance that climate change will contribute 30 cm by 2050 and 65 cm by 2100. These estimates do not include sea level rise caused by factors other than greenhouse warming."

Overall, Titus and Narayanan (1995) concluded that sea level is likely to rise less than estimated by earlier studies. The lower estimates reportedly result from a downward revision of future temperatures, and growing consensus that Antarctica will probably not add to sea-level rise in the next one hundred years. Also, recent revisions in carbon cycle models have lowered estimates of CO_2 concentrations. Carbon "sinks" continue to be the subjects of intensive research. For example, Sabine, et al. (1997) estimated that the oceans remove about 37 percent of the CO_2 produced each year from the burning of fossil fuels. This estimate is being improved by a program of direct measurements of carbon in seawater. The oceans naturally contain much more carbon than the atmosphere, mostly in the form of bicarbonate ions (Sabine, et al., 1977).

DeWispelare, et al. (1993) reported the results of an expert elicitation study on future climate in the YM region. Three of five climate experts believed that the principal greenhouse warming effects might last about 3-5 kyr. The other two experts believed that anthropogenic effects could last significantly longer. In fact, one researcher stated (DeWispelare, et al., 1993, p. H-63) that "Human induced atmospheric and surface changes (e.g., greenhouse gas changes, land surface alterations including increased agriculture, and absolute human population growth) will lead to such dramatic climate changes that the paleoclimate record will not be the key to the distant future."

The staff recognizes that, in the end, predictions about the manner and degree to which human activities would affect climate in the distant future will remain highly uncertain. Anthropogenic effects could significantly influence world climates during the next several thousand years. However, realistically, there are limits on how long greenhouse warming can last. After fossil fuels are depleted the natural carbon sinks will gradually remove excess amounts of CO_2. Therefore, the staff's current view is that there is no reason to presume that anthropogenic effects will be of sufficient magnitude and duration to indefinitely postpone a new glacial cycle. More importantly, with respect to a safety analysis of YM, it would not be conservative to presume that present-day conditions will persist for 10 kyr or longer. Instead, the presumption that cooler and wetter conditions will return promotes analyses that are more challenging to repository performance. These kinds of analyses are needed to provide confidence in the results of a HLW safety analysis.

In summary, predictions about the magnitude and duration of future anthropogenic changes in world climates are expected to remain highly uncertain. However, for purposes of evaluating repository performance, it is both pragmatic and conservative to postulate that such changes will be relatively short (several thousand years at most) and that global cooling will return, gradually leading to the next glacial stage. That would lead to pluvial climatic conditions at YM which, as in the past, would be generally cooler and wetter than today's climate.

- Climate Models and High-Level Waste

Various national and international efforts, such as those of the World Climate Research Programme, are analyzing climate change through the development of general circulation or global climate models (GCMs), intercomparison of model results, and the acquisition of paleoclimatic data. For example, 29 atmospheric GCMs participated in the Atmospheric Model Intercomparison Project (Gates, 1992). GCMs have considerable societal value in studying the potential effects of deforestation and burning of fossil fuels, etc., on global and regional climate patterns. Possible benefits of global warming will not be addressed here. Global warming could have various adverse consequences, such as increasing the prevalence of drought conditions in grain-producing regions or increasing the numbers and intensities of tropical storms. Over the next several centuries sea level may rise enough to inundate coral atolls and low-lying continental coasts and cities around the world. Portentous as these possibilities are, they are not relevant to potential HLW disposal at YM unless they would indirectly lead to higher rates of groundwater infiltration.

Timbal, et al. (1997) describe a continuing multi-phase project that seeks to improve GCM results by better integrating land-surface and atmospheric models. Nonetheless, attempts to use GCMs to predict climatic changes over tens of thousands of years would almost certainly remain controversial, leading to debate over the competence of one model and data set vs. another. Heated debates have even arisen over studies of present-day anthropogenic effects on climate (Risbey, et al., 1991a,b; Schlesinger and Jiang, 1991a,b,c; Bolin, 1992; Harvey, 1992; Oeschger, 1992; Schlesinger, 1992;

Feder, 1996). A staff concern is that GCM results could be used to suggest that greenhouse warming might postpone the return of pluvial conditions at YM for more than 10 kyr. The staff considers GCM predictions inadequate to support such a claim. Efforts to validate GCMs will likely result in continual model calibration. These difficulties, along with known limitations of GCMs (Stone and Risbey, 1990), have led the staff to conclude that climate modeling will not be required to support HLW licensing. Instead, a more direct approach is available.

- Representation of Future Climate at YM

With respect to a HLW repository, the staff considers that it is adequate to forecast and bound future hydrologic conditions by studying conditions during past pluvial climates (Coleman, et al., 1996). This kind of work has included the collection and interpretation of regional and global paleoclimatic data to better understand the past range of climates at YM. The data include information from paleodischarge sites, packrat (*Neotoma*) middens, pollen studies, paleolake levels and sediments, groundwater isotopic data, soil properties, tree rings, erosion studies, and other sources. These data are often used to calibrate GCMs, but they can be used directly to bound past climates.

Given the difficulties and realities outlined above, and the need to proceed with realistic performance assessments, the staff recommends a pragmatic approach to address climate change and its effects. Current information does not support an assumption that the present-day climatic regime at YM will persist unchanged for 10 kyr or more. Therefore, it will be presumed, based partly on the results of a climate expert elicitation that the staff sponsored, that an enhanced greenhouse warming will last at most several thousand years, and that about 3 kyr in the future the climate at YM will resume or continue the global cooling predicted by the Milankovitch orbital theory of climate. In other words, anthropogenic effects will be assumed to delay but not prevent an inevitable return to pluvial conditions at YM.

To ensure realism in its safety analysis, staff will postulate that full pluvial (cooler and wetter) conditions will dominate at least several thousand years of the next 10 kyr. Such conditions would be reasonably challenging to repository performance because groundwater fluxes through a repository are expected to be higher during pluvial episodes. The staff's presumption is somewhat conservative if, as appears to be the case, full pluvial conditions at YM are associated with the onset, duration, and waning of glacial maxima in the northern hemisphere. In reality the paleorecord shows that much more than 10 kyr are needed for glacial stages to reach their maxima. There is another safety benefit that accrues by presuming full pluvial conditions will recur. It recognizes the possibility that unforeseen human effects or the natural recovery of global climate from these effects could cause cooler and wetter conditions at YM than otherwise expected. And finally, any safety analysis that covers time periods longer than 10 kyr into the future should simulate climate change using 100 kyr cycles of glacial/interglacial stages, similar to those seen in the paleoclimate record.

This approach to climate representation is consistent with the findings of Dansgaard, et al. (1993), who reported evidence for general instability of past climate based on ratios of stable oxygen isotopes in Greenland ice cores. They raised the question of whether the Holocene will remain stable despite anthropogenic effects. No other period during the last 250 kyr has apparently enjoyed such a stable climate. This climate approach is also consistent with Milankovitch cycles, because a minimum in northern-hemispheric summer insolation will occur during the next 10-15 kyr, based on the solar insolation curves of Vernekar (1968, 1972) as reproduced in part by Lamb (1977). A summer insolation high equivalent to the one centered around 11-kyr B.P. will not recur at northern latitudes

>45° during the next 105 kyr (Lamb, 1977, pp. 314-315). The next substantial peak in summer insolation at these latitudes is predicted to occur about 65-75 kyr in the future. Updated solar insolation calculations have been performed by A. Berger and others, and these should be used to evaluate time periods greater than 50-100 kyr after present (AP), if necessary (see references in Winograd, et al., 1992, note 22).

The assumption that pluvial conditions will return to YM during the next 10 kyr has the advantage that useful estimates of future climate can be obtained even though the scientific debate about the causes of climate change continues unabated. This approach clearly demonstrates that conditions challenging to repository performance will be considered in performance assessments because these conditions would invoke higher rates of precipitation and groundwater infiltration than are occurring at the site today. Such an approach is consistent with conclusions reached by the National Research Council (1995, p. 9), which concluded that the probabilities and consequences of climate change (and other processes) are sufficiently boundable that these factors can be included in performance assessments that extend over a time frame of 10^6 years.

- Comments by the U. S. Nuclear Waste Technical Review Board (NWTRB)

The NWTRB discussed climate issues in a report to the U.S. Congress and the Secretary of Energy (NWTRB, 1993). Chapter 3 of that report was entitled "Resolving Difficult Issues - Future Climates." They stated (p. 55) that

> While there is no guarantee that future climatic and hydrologic states will be similar to those in the past, the Board believes that it is appropriate to assume that the paleoclimatic and paleohydrologic data base (to the extent that it is both sufficiently accurate and complete) can serve as an excellent foundation for predicting the range of these future states at Yucca Mountain...however, this assumption falls short when trying to assess the impacts of modern industrial society on future climate.

The NWTRB report also states (p. 57) that "Past analogues of future greenhouse-gas-changed climate have not been found. Thus while paleoclimates can assist in building confidence by hindcasting, they cannot yet be used as predictions of regional climate change due to future increases in greenhouse gases." With respect to GCMs, the report states that (p. 57)

> ...it is unclear at what time in the future climate models will be sufficiently mature to provide confident detailed long-term predictions of climate at regional and local scales, such as those associated with the Yucca Mountain site. Climate models could, however, provide valuable insights as to the processes affecting future climate, the likelihood of past climate states occurring in the future, and, perhaps, most importantly, the occurrence of climate states such as the enhanced greenhouse effect, which are not reflected in the paleoclimate data base.

One of the NWTRB's (1993, p. 59) recommendations was that "Future climate states should be estimated primarily through the use of paleoclimatic and paleohydrologic data. Numerical modeling can play a supplementary, but important, role in overcoming the limitations of the paleoclimate data and estimating the likelihood of adverse climate states." The NWTRB also states (p. 58) that DOE will have to "...decide when it has reached the point of diminishing returns with respect to its climate-related studies.... The key element in this decision should not be the ability to predict future climate

at Yucca Mountain, but rather the ability to determine, with sufficient confidence, whether future climate states will or will not cause the repository to fail."

The staff generally agrees with the NWTRB (1993) report, although it believes that enough information is already available to reasonably estimate the range of future climates at YM and to analyze their effects on repository performance. DOE's current use of climate modeling can provide additional information, but the staff will not require such work to estimate the range of future climatic conditions at YM over many thousands of years.

4.2 Effects of Climate Change

It will be necessary for DOE to develop one or more representations of future climate, to estimate the ranges of future precipitation, temperature, and water-table rise at YM. Water-table rise would clearly be an "effect" of the climate changing to cooler and wetter conditions. Changes in precipitation and temperature will be discussed as though they were also "effects" of climate change, but the staff recognizes that climate itself is largely defined by prevailing conditions of precipitation and temperature. Staff will review DOE's future climate representations to determine whether they are consistent with known trends of past climatic variation. The following *Acceptance Criteria* apply:

- Bounding values of climate-induced effects (for example water-table rise) based primarily on paleoclimate data will be acceptable. Staff should determine whether DOE has made a reasonably complete search of paleoclimate data pertinent to water-table rise and other effects (for example, changes in precipitation and geochemistry) of climate change that are available for the YM site and region, and has satisfactorily documented the results. In evaluating DOE's analyses, staff should determine whether, at a minimum, DOE has fully considered information contained in Paces, et al. (1996), Szabo, et al. (1994), Forester, et al. (1996), and other reports that may become available.

- It will be acceptable for DOE to use regional and sub-regional models for the saturated zone to predict climate-induced consequences if these models are calibrated with the paleohydrology data. Staff should determine whether DOE's models of the consequences of climate change are consistent with evidence from the extensive paleoclimate data base. Specifically, climate-induced water-table rise is expected to occur in response to elevated precipitation during future pluvial climate episodes, and the staff should determine whether DOE's estimates of climate-induced water-table rise are consistent with the paleoclimate data. The currently known estimate of water-table rise during the late Pleistocene is 120 m (394 ft). Staff should determine whether DOE's assumptions about climate-induced water-table rise over 10 kyr, if different from 120 m (394 ft), are adequately justified.

- Based on staff judgment and analysis, determine whether DOE has adequately incorporated future climate changes and associated effects in its performance assessments. Current information does not support an assumption that present-day climate will persist unchanged for 10 kyr or more. The staff should keep in mind that the consequences of climate change may be coupled to other events and processes and therefore the projections of water-table rise that are used in total system performance may be different from those based solely on climate change.

4.2.1 Technical Bases for Review Procedures and Acceptance Criteria (Climate Change - Future Precipitation and Temperature)

Recent published work suggests that future pluvial climates could experience an MAP upper threshold that is significantly greater than present-day MAP. Various researchers have used paleoecological methods to estimate the range of MAP and MAT during the late Quaternary in the Great Basin. Forester (1994, p. 2750) stated that "Preliminary estimates from fossil plant and animal records suggest that during the last glacial (14 to 25 ka [kyr]) mean annual precipitation may have been as much as five times modern, while mean annual temperatures were 8-10 °C lower than today." Forester and Smith (1994) studied fossil ostracodes from deposits in the upper Las Vegas Valley. They concluded (p. 2560) that "...during the late Pleistocene average climate conditions in southern Nevada may have been about four times wetter than today and perhaps as much as 10 °C colder." In a presentation to the U.S. Nuclear Waste Technical Review Board, Forester (1996, p. 18) stated that "During the last glacial within 100 miles of YM, MAP likely varied from about 15 to more than 20 inches at some localities between 5 and 6 k feet with as yet unknown standard deviation and regional variability." This estimated range of MAP (380-510+ mm, or 15.0-20.1 in) is roughly two to three times the present-day MAP of 150-160 mm (5.90-6.30 in)(DOE, 1988b, p. 5-17).

Morrison (1996) forecasts that, consistent with the last interglacial/glacial transition, the coming transitional period will consist of repeated extreme changes in global climate. He concludes that the southern Great Basin will experience frequent episodes with order-of-magnitude increases in effective precipitation, flood magnitudes, and erosion rates. Based on a discussion with staff, Morrison defines effective precipitation as effective moisture, which is the residual precipitation (not lost to evapotranspiration) that contributes to surface-water runoff and groundwater recharge.

Mifflin and Wheat (1979) noted that there is evidence for 53 pluvial lakes of Wisconsin age in Nevada. They studied the variability of modern climates and hydrologic regimes in the Great Basin to infer what conditions were like during past pluvials. Mifflin and Wheat (1979, p. 5) concluded that "...the observed pluvial lake paleohydrology could have been maintained by: a) mean annual temperatures approximately 5 °F lower than those of today; b) by corresponding pluvial mean annual precipitation averaging 68 percent over modern precipitation; c) by mean annual pluvial lake evaporation averaging 10 percent less than mean annual modern lake evaporation." Mifflin and Wheat (1979) also summarized conclusions of earlier, pioneering researchers who studied paleoclimates in the Great Basin.

Mifflin (1990) described the regional hydrologic effects of past pluvial climates in the YM region. Based on the extent of former pluvial lakes in the Great Basin, effective moisture (runoff and recharge) was elevated by about an order of magnitude over modern conditions, and regional water tables rose as much as several hundred feet. That would be consistent with the findings of Oviatt (1997) who described climatic fluctuations of Lake Bonneville for the period from 30 to 10 kyr B.P. This period includes the Wisconsin glacial maximum. Lake Bonneville was the largest of the late Pleistocene pluvial lakes, located in northern Utah in the northeastern portion of the Great Basin.

Spaulding (1985, p. 50) estimated departures of MAT and MAP for various intervals from 45 to 10 kyr B.P. He estimated that MAP during the Wisconsin glacial maximum (around 18 kyr B.P.) was 30 to 40 percent greater than modern. Spaulding (1990) described contrasts between Middle and Late Wisconsin fossil records. He found that mesophytic species (plants needing moderate amounts of moisture) appear to have been more abundant during the Middle Wisconsin, while steppe shrubs

appear dominant during the Late Wisconsin. Spaulding concluded that effective moisture and temperature may therefore have been lower during the late Wisconsin, especially during the glacial maximum ca. 18 kyr B.P. Referring to the glacial maximum, Spaulding (1990, p. 1255) concluded that "An estimated increase in average annual precipitation (Pa) of 40% is all that is required to account for the paleobiotic record in this [YM] region. With the fossil record dominated by xerophytic species [plants tolerant of dry habitats] it is difficult to see how the increase could have been greater."

Spaulding (1995) summarized past climatic conditions at YM based on paleoecological data accumulated to date.

- In the YM region, maximum recharge occurs during warmer climatic intervals (interstadials). The last occurred between ca. 14 kyr and 8 kyr B.P. and was characterized by long-term increases in MAP of up to 100 percent. Short-term (decadal to century) departures of MAP may have approached 400 percent of modern values.

- The Wisconsin glacial maximum (ca. 18 kyr B.P.) was cold and dry, with a decline in MAT of about 7 °C (13 °F) and an increase in MAP of about 40 percent.

- The period ending around 23 kyr B.P. (unit D time) had higher MAP (and recharge) than later periods. This period was characterized by more common deep-water environments in valley bottoms, and early episodes with poorly constrained ages were as wet or wetter.

Wigand, et al. (1994) documented late Holocene climate shifts at various sites in the Great Basin. Their main conclusion was that shifts to times of higher effective moisture were not accompanied by rapid shifts in plant communities. The result was a lag time during which there was less competition for water and greater opportunities for groundwater recharge. There was more competition for moisture and less recharge after plant communities adjusted to the wetter conditions. Wigand, et al. (1994, Figure 2) also presented evidence from Tule Springs (upper Las Vegas Valley) and from various mountain sites that suggests MAP was 2-3 times higher than today from 18 kyr to >23 kyr B.P.

An NRC-sponsored study elicited the opinions of five experts regarding climate change over the next 10 kyr (DeWispelare, et al., 1993). In the next 10 kyr, one expert predicted a doubling of precipitation; one foresaw 15 percent less precipitation; and three others ranged from no change in precipitation to 30-40 percent increases over the present. The experts believed that the montane rain shadow that dominates the Great Basin climate would continue to exert a strong regional influence. A discussion of the rain shadow and its long-term effect is given by Winograd and Szabo (1988).

The milestone report produced by Forester, et al. (1996, p. 33) provides estimates of MAP for 8 intervals over the period from 12 kyr to 35 kyr B.P. They draw several conclusions with respect to past precipitation and effective moisture (p. 65).

> Effective moisture throughout the last glacial was greater than present, but the reasons for its increase differed. In the cool wet periods, gains in MAP probably played as important a role as those [declines] in MAT. During the cold dry periods substantial depressions in MAT with

only modest gains in MAP probably explain the greater levels of effective moisture. Average gains in MAP appear to be about 1.5X to 2X modern, with an unknown standard deviation. Present MAP standard deviations are about fifty percent of the mean value, which, if applicable to the past, would place typical MAP in a range from modern-like to about 3X present MAP. The white fir episodes likely had higher mean MAP. Depressions in MAT appear to range from about 5 to perhaps more than 10 °C below modern. Refinement of past MAP and MAT estimates in both time and space and determining the standard deviations about those means remains a key item to be completed.

These MAT and MAP conditions representing a pluvial climate at YM are similar to the present-day climate in northern Nevada and eastern Oregon, based on data from the U. S. Geological Survey (USGS) (1970). The following table summarizes the precipitation increases during past pluvials as estimated by various workers:

Forester, et al., 1996	YM region	Average gains in MAP appear to be about 1.5X to 2X modern, with unknown standard deviation (range from modern-like to about 3X modern).
Forester, 1996	Area within 100 miles (161 km) of YM	Roughly two to three times modern MAP during last glacial.
Morrison, 1996	Southern Great Basin	Order of magnitude increase in recharge [effective moisture] - implies at least 100 percent increase in MAP.
Spaulding, 1995	YM region	Latest Wisconsin to early Holocene: up to 100 percent increase in MAP (short-term increases in MAP near 400 percent of modern). Glacial maximum: about 40 percent increase in MAP. Middle Wisconsin: greater MAP and recharge than later periods.
Forester, 1994	YM area	Up to five times modern MAP.
Wigand, et al., 1994	Various Great Basin sites	MAP 2-3 times higher than modern (from 18 kyr to >23 kyr B.P.).
Forester and Smith, 1994	Upper Las Vegas Valley	Late Pleistocene average conditions about four times modern MAP.
DeWispelare, et al., 1993 (elicitation of five expert opinions)	Vicinity of YM	For 10 kyr future period, one estimate was 15 percent less precipitation; three estimates were for no change or 30-40 percent increase; and one expert foresaw doubling of precipitation.

Mifflin, 1990	YM region	Order of magnitude increase in effective moisture (runoff and recharge) compared with present-day climate.
Spaulding, 1985	YM region	Over the period from 39 to 10 kyr B.P., MAP increases ranged from 10 to as much as 40 percent higher than modern.
Mifflin & Wheat, 1979	Basin areas of former paleolakes	About 70 percent increase over modern MAP.

The staff have noted an apparent convergence of professional opinions regarding precipitation during past pluvials. For example, higher estimates of MAP have been revised downward, from about 5 times modern MAP (Forester, 1994) to a factor of 2 to 3 (Forester, 1996; Forester, et al., 1996). Lower estimates have been revised upward (Spaulding, 1985; Spaulding, 1995). The revised MAP estimates approach that by Wigand, et al. (1994) and are more consistent with the estimates provided by other workers. The staff has determined that MAP during past pluvials at YM is the best indicator of what to expect during future pluvial climates. This kind of information can be used to estimate a range for future pluvial MAP, which can further be used to estimate rates of infiltration and deep percolation.

Compared with Wisconsin conditions, groundwater recharge has been significantly reduced during the Holocene interglacial. This is best illustrated by the disappearance or dramatic reduction in size of pluvial lakes. There is no reason to believe that future pluvial climates will not be similar to those of the Wisconsin glacial stage. Since glacial stages last longer than interglacials, future climates at YM will be wetter than today most of the time. Based on currently available information, the NRC staff has determined that the potentiometric data from Brown's Room in Devils Hole provide the best available indicators of the duration of higher recharge conditions in the Great Basin during the Wisconsin (Szabo, et al., 1994).

4.2.2 Technical Bases for Review Procedures and Acceptance Criteria (Effect of Climate Change - Water-Table Rise)

There are various lines of evidence that bear on past water-table stands at YM. Taken as a whole they can be used to define a reasonable upper limit to which the water table may rise in response to increased recharge under future pluvial conditions.

- Location and nature of paleospring deposits known as the Lathrop Wells diatomites

Quade (1994) and Quade, et al. (1995) studied fossil spring deposits over a large part of the southern Great Basin. From their survey of fine-grained sediments in this region, they concluded that the deposits were associated with elevated water tables and increased groundwater discharge at various times during the Pleistocene. At various locations inferred water-level changes since late Wisconsin time vary from as little as 15 m (49 ft) to as much as 95-115 m (312-377 ft). One set of paleospring deposits is located only 20 km (12 mi) SW of YM in the southern part of Crater Flat. The nature and position of these diatomites suggests that the water table may have been as much as 115 m (377 ft) higher during the Pleistocene. The water table may have been at or near ground level as recently as

12 kyr ago. The deposits contain mudstones and diatomites, and have been informally named the Lathrop Wells diatomites by Quade, et al. (1995).

Previously, Paces, et al. (1993) estimated ages for several of the Lathrop Wells Diatomites. Using uranium-series disequilibrium, they determined that the deposits represent active springs at 18 ± 1, 30 ± 3, 45 ± 4, and > 70 kyr. They found that two samples from different sites yielded identical ages, suggesting that the springs may have been contemporaneous and were likely part of the same hydrodynamic system. Uranium isotopic compositions suggested that groundwater from the regional Tertiary-volcanic aquifer was the source of the spring flow, and that the water table had formerly risen 80-115 m (262-377 ft) above present levels and may have fluctuated repeatedly. Forester (1996), in a presentation to the NWTRB, noted that analysis of the diatomite deposits (Horsetooth Site) suggests groundwater discharge from the regional aquifer and from a perched flow system.

Stuckless (1994) discussed dating of the diatomite deposits in a presentation to NRC's Advisory Committee on Nuclear Wastes (ACNW). The apparent ages of one deposit range from 16 kyr to 133 kyr, with six sample ages occurring in the interval of the last glacial maximum, broadly 15 to 21 kyr B.P. Another deposit yielded dates of 12 kyr to 28 kyr B.P. The two youngest dates represent the latest Wisconsin. Stuckless caveated the data as preliminary and predecisional.

Additional details about the Lathrop Wells Diatomites and their estimated ages were described by Paces, et al., 1996. They found evidence that the deposits were formed during two distinct periods, from about 15 to 60 kyr and an older episode of 90 to 180 kyr. They report that isotope and paleontological data rule out a surface-water source for the deposits. Drainage from perched-water systems was also discounted as a source. Paces, et al. (1996, p. 1) found that

> ...regional, saturated-zone ground water most likely supplied discharge during pluvial episodes. This conclusion requires the regional water table to fluctuate up to about 100 to 120 m between pluvial and interpluvial periods. Fluctuations of the same magnitude occurred over the last two glacial cycles...much of the late Pleistocene was characterized by higher water tables (as much as 60 to 80% of the last 200 ka [kyr]). Therefore...it is anticipated that this hydrologic state will recur in the future.

The staff recognizes that the exposed setting of the Lathrop Wells Diatomites could cause geochemical open-system behavior, an adverse factor in radiometric dating. However, parts of these deposits are certainly Pleistocene in age, as suggested by radiometric dating, because fossil remains of mammoth (*Mammuthus*) have been found there (Quade, et al., 1995).

Modern-day groundwater is about 115 m (377 ft) lower than the paleospring deposits. Consistent with Paces, et al. (1993), Quade (1994) and Quade, et al. (1995) noted that if water table gradients were similar to modern-day gradients, then a 115-m (377 ft) rise could be extrapolated to YM. This degree of rise could possibly be used to define a reasonable upper limit for rise of the water table at YM during future pluvial climates. Such a rise would significantly reduce the thickness of the unsaturated zone barrier at YM, but it would not saturate a hypothetical repository in the Topopah Spring tuff. A water-table rise of this magnitude would generate spring flow in areas south of YM, which would provide surface drainage outlets for groundwater and perhaps reduce the potential for greater rise.

The staff recognizes that there is continuing discussion about the nature and age of the Lathrop Wells Diatomites. However, they should be interpreted as evidence of former water-table rise unless compelling evidence becomes available to prove that the deposits resulted entirely from the surface discharge of perched water. It is remotely possible that similar, undiscovered deposits may exist at higher altitudes and closer to YM. However, it seems unlikely that such deposits would have escaped the notice of geologists and soil scientists who have extensively mapped the region.

- Strontium isotopic evidence for calcites in the unsaturated zone

Marshall, et al. (1993) compared strontium isotope ratios for five different types of samples, including the paleospring sites, pedogenic (or near-surface) calcites, fracture-fill calcites from the unsaturated and saturated zones, and groundwater from the Tertiary aquifer. The fracture calcite samples came from five boreholes at YM. The calcites in the unsaturated zone have strontium ratios almost identical to the pedogenic calcites, suggesting that they have a similar origin. The only exceptions are four samples from fractures about 85 m (280 ft) above the water table in hole G-2. These four samples have strontium ratios that suggest a significant non-pedogenic component as a source for their strontium. Their strontium ratios are similar to those found in groundwater from the Tertiary tuff aquifer. Based on this, Marshall, et al. (1993) concluded that the water table may have been about 85 m (280 ft) higher than now. This amount of suspected water table rise is of similar magnitude to and corroborates that estimated from the paleosprings to the south (Paces, et al., 1996). Marshall, et al. (1993) also noted that fracture-filling calcites from above and below the water table show different colors under ultraviolet light. Unsaturated zone calcites have a white to purplish fluorescence, whereas those from the saturated zone fluoresce from pink to orange.

- Glassy nonwelded material thins and disappears where the basal Topopah Spring occurs close to the water table

Bish and Vaniman (1985) used X-ray diffraction methods to study mineral distributions in tuffs at YM. They prepared cross-sections to show the distribution of minerals and glassy, or vitric, material. Their work was updated a few years later by Bish and Chipera (1989). An interesting pattern was found in the disappearance of vitric material in the tuffs. Below the dark layer of volcanic glass that forms the basal vitrophyre of the Topopah Spring is the Calico Hills non-welded tuff. The top of the Calico Hills contains abundant pumice and glassy shards in voids. This vitric zone occurs just below the vitrophyre. However, closer to the water table the glassy material mostly disappears. Bish and Vaniman state that the glassy material has been progressively altered to zeolites where the zone is closer to the water table. Based on the data from Bish and Vaniman (1985) and Bish and Chipera (1989), it appears that the base of the glassy (vitric) tuff is about 80-100 m (262-330 ft) above the current water table. This suggests to the staff that the water table was previously higher than now for extended periods, especially since the alteration process may have required thousands of years. The data do not indicate when the water table was higher, but do suggest that the water table may have risen no more than about 100 m (330 ft) higher than at present.

Levy (1991) further discussed the use of geochemical indicators in nonwelded tuffs to interpret paleohydrology. She notes that most zeolites in these tuffs appear to be products of diagenetic alteration in which zeolites were precipitated when the original glassy material dissolved at ambient temperatures in a water-rich environment. Levy suggests that zeolitization may require time periods on the order of 10 kyr, and that much of the zeolitization may have occurred long ago. The static

water level (SWL) is presently about 100 m (330 ft) below the glassy-zeolitic boundary, a stratigraphic transition zone that is about 10 m (33 ft) thick. Levy (1991) states (p. 482) that

> ...the vitric-zeolitic transition in the central-eastern part of Yucca Mountain probably marks the highest SWL established at the mountain during the last 12.8 myr. The SWL remained at its highest position no more than 1.2 myr. Subsequent water levels may have existed at higher elevations than the present SWL (about 120 m below the zeolitic transition in [well] G-4), but have not been any higher than 16 m below the zeolitic transition and perhaps no higher than 59 m below the transition (adding the 43-m thickness of the devitrified zone in H-6 to the 16-m depth of glassy tuff below the transition).

Levy also stated that, compared to mineralogic changes, features such as paleospring mounds are more direct indicators of former hydraulic conditions because they were formed by aqueous transport and deposition. Levy (1991) concluded that the highest groundwater levels were reached and receded downward 11.6 to 12.8 million years ago, and since that time the water level at YM has probably not risen more than about 60 m (200 ft) above present levels. DOE (1992, p. 2-66) cites Levy's (1991, p. 2-66) estimate that the water table has probably not been higher than 60 m (200 ft) above its present level for prolonged periods. However, Levy's work occurred before more recent studies of the Lathrop Wells Diatomites that suggest higher potential rises of the water table.

- Other geochemical evidence

Quade and Cerling (1990, p. 1549), writing in the journal Science, reached the following conclusions:

> Comparison of the stable carbon and oxygen isotopic compositions of the fracture carbonates with those of modern soil carbonates in the area shows that the fracture carbonates are pedogenic in origin and that they likely formed in the presence of vegetation and rainfall typical of a glacial climate. Their isotopic composition differs markedly from that of carbonate associated with nearby springs. The regional water table therefore remained below the level of Trench 14 [located on the eastern side of YM] during the time that the carbonates and silica precipitated, a period probably covering parts of at least the last 300,000 years.

- Presence of a perennial paleodischarge site in Fortymile Wash

To the northeast of YM there is paleoecological evidence of higher recharge and precipitation in the past. A perennial discharge site existed in Fortymile Canyon about 50 kyr ago. Spaulding (1994) and others have studied ancient packrat nests, or middens, in the region. Modern-day packrats have a foraging radius of < 50 m (164 ft), and materials preserved in the fossilized nests of their ancient ancestors can help identify local assemblages of prehistoric plants.

Spaulding and others (1994) found a set of ancient middens in northern Fortymile Canyon. They occur near the UE-29 boreholes about 12 km (7.4 mi) northeast of YM. Most of these ancient middens have carbon isotope ages of 13 to 22 kyr and contain no evidence of water-loving plants. But one midden was much more ancient, about 50 kyr or older (at the limit of radiocarbon dating), and contained remains of willows (*Salix*), knotweed (*Polygonum*), and wild rose (*Rosa*). These plants must have constantly damp soil or proximity to the water table to survive and reproduce (see the description of indicator plant species described by the National Research Council, 1992, p. 208-211). Spaulding (1994) refers to this older midden site as FMC-7, or Fortymile Canyon sample #7. It is on

the eastern flank of Fortymile Wash about 60 m (200 ft) above the Canyon floor. The site is about 460 m (1510 ft) north of wellsite UE-29. At this location the water table is presently more than 400 m (1310 ft) higher than at YM. The water table at UE-29 is shallow, only 27 m (88 ft) deep, because this area is north of the so-called zone of high hydraulic gradient. At this canyon site a modest water table rise of less than 30 m (100 ft) could generate spring flow in Fortymile Wash. Based on the location of FMC-7, inferred erosion rates, present-day groundwater elevations, and fossil plants, Spaulding (1994) concluded that the water table was 75 to 95 m (246 to 312 ft) higher during the period from 73 kyr to 47 kyr B.P.

- Inferences based on the extent of paleolakes

Mifflin (1990) described the regional hydrologic effects of past pluvial climates in the YM region. Based on the extent of former pluvial lakes in the Great Basin, effective moisture (runoff and recharge) was elevated by about an order of magnitude over modern conditions, and regional water tables rose as much as several hundred feet.

- Timing in changes of potentiometric levels of the carbonate aquifer at Devils Hole

Winograd and Szabo (1988, p. 151-152) stated that '...the continuing uplift of the Sierra Nevada...and Transverse Ranges, and lowering of Death Valley...relative to surrounding regions, should result in a continued progressive decline of the regional water table in the next 100,000 to 1 million yr (and beyond?) in response to increasing aridity and to lowering of ground-water base level." However, Winograd and Szabo (1988, p. 151) noted that their suggestion of a long-term lowering of the regional water table does not preclude relatively rapid fluctuations in response to pluvial climates of the Pleistocene, as indicated by data from Devils Hole in the Amargosa Desert.

There is solid evidence from Devils Hole of a Wisconsin-age rise of potentiometric levels in the Paleozoic carbonate aquifer. Szabo, et al. (1994) reported a record of water-table fluctuations in Brown's Room at Devils Hole. Their data are extensive enough to suggest that the water table may have been more than 4 m (13 ft) higher than present-day levels throughout the Wisconsin. They specifically conclude that the paleo-water table stayed more than 5 m (16 ft) above present levels between about 116 kyr and 53 kyr ago, that the level fluctuated between about +5 m (16 ft) and +9 m (+30 ft) from 44 kyr to 20 kyr ago, and then declined rapidly from about +9 m (+30 ft) to its present level during the last 20 kyr. Szabo, et al. (1994) considered climate change to be the main cause of the water-table fluctuations over the last 100 kyr.

The water-level changes at Devils Hole relate only to the Paleozoic carbonate aquifer within the Ash Meadows groundwater basin and cannot be used to determine water levels in other aquifers. But groundwater levels in this regional aquifer must exert a major control on water levels in overlying tuff and valley-fill aquifers. Because the Ash Meadows groundwater basin is very large, Szabo, et al. (1994, p. 68) suggested that the data from Brown's Room "may record the timing of regional hydrologic changes that occurred in the southern Great Basin." The staff agrees with this, and believes that the timing of significant water-level fluctuations at YM should correlate reasonably well with those at Devils Hole. This is reasonable even though YM and Devils Hole may exist in different subbasins of the regional Death Valley groundwater flow system (Laczniak, et al., 1996). The fact that the water table at YM may have risen 10 times higher than at Devils Hole would not be unusual, because of the proximity of YM to areas of higher elevation where recharge would have been

enhanced. Higher transmissivities in the Paleozoic carbonate aquifer would also result in smaller fluctuations of the potentiometric surface at Devils Hole.

The staff's views about water-table rise are strongly influenced by the fact that paleoclimatic indicators throughout the Great Basin are reasonably consistent. For example, the Wisconsin-age high stands measured at Devils Hole are consistent with a long-duration high stand of Searles Lake, and with the reported dates of paleospring flow at the Lathrop Wells Diatomites. Likewise, there is reasonable correlation between proxy paleoclimatic records for Searles Lake, Las Vegas Valley, Grand Canyon travertine, south-central Nevada plant records, and Brown's Room at Devils Hole (Szabo, et al., 1994). A high stand of Lake Manley in Death Valley (Li, et al., 1996, Fig. 16) also coincides with the general timing of high stands of Searles, Lahontan, and Bonneville Lakes, and with a high groundwater stand in Devils Hole. Long-term records of paleolake levels in particular show important differences that must be related to local hydrologic conditions. For example, Lake Manly was the last in a chain of "overflow" lakes, and it therefore did not always receive a substantial surface-water influx.

Szabo, et al. (1994) and other investigators have noted inconsistencies in the paleoclimatic data that have yet to be explained. But in general, except for the temperature proxy data from Devils Hole, the paleoclimatic data are discontinuous and only provide "snapshots" of prevailing conditions at various sites and times. The well-dated, relatively continuous 500-kyr record of paleotemperatures from Devils Hole (Winograd, et al., 1992) is one of the best paleoclimate records in existence and has been used to link past climate change in the Great Basin to changes elsewhere. The staff has determined that this and other paleoclimate records could reasonably be used to estimate the likely range of future climate variability at YM.

- Inferences from hydrologic modeling of the saturated zone flow system

Czarnecki (1985) used a finite-element model to simulate the effects of a future increase in precipitation and recharge on water levels. He concluded that a doubling of precipitation could lead to a 15-fold increase in recharge and a water-table rise of 130 m (426 ft) beneath YM. Although Czarnecki's (1985) work suggests that water-table rises greater than 120 m (394 ft) are not impossible, the preponderance of field evidence suggests that the water table has not risen more than 120 m (394 ft) above present levels for extended periods since the deposition of the volcanic tuffs. The Paintbrush and Calico Hills tuffs were deposited more than 10 million years ago (DOE, 1988a, p. 1-56).

Ahola and Sagar (1992) developed a regional flow model and analyzed various phenomena that could influence the regional water table. They estimated that a water-table rise of about 75-100 m (246-330 ft) could occur in response to a 10-fold increase in groundwater recharge. This particular analysis included a zone of enhanced recharge that represented Fortymile Wash. They concluded that the water table near Yucca Mountain is relatively sensitive to variations in recharge along this wash.

The following table briefly summarizes the degree of former water-table rise that has been estimated by various workers:

Forester, et al., 1996	YM and southern Nevada	Up to 100-120 m (330-394 ft) at various times during the last two glacial cycles.
Paces, et al., 1996	Lathrop Wells Diatomites, SW of YM	100-120 m (330-394 ft) (data suggest elevated regional water tables as much as 60-80 percent of the last 200 kyr).
Quade, Mifflin, et al., 1995; Quade, 1994	Lathrop Wells Diatomites, 20 km (12 mi) SW of YM	< 115 m (377 ft)
Szabo, et al., 1994	Brown's Room, Devils Hole (Ash Meadows - Paleozoic carbonate aquifer)	up to +9 m (30 ft)
Spaulding, 1994	Fortymile Canyon NE of YM (FMC-7 packrat midden site)	75-95 m (246-312 ft)
Paces, et al., 1993	Lathrop Wells Diatomites, SW of YM	80-115 m (262-377 ft)
Marshall, et al., 1993	YM boreholes	< 85 m (280 ft)
Ahola & Sagar, 1992	YM (regional groundwater model)	75-100 m 246-330 ft)
Levy, 1991	YM boreholes	< 60 m (200 ft)
Mifflin, 1990	YM region	Less than 100 m (up to several hundred feet in the YM region).
Bish & Vaniman, 1985; Bish & Chipera, 1989	YM boreholes	< 100 m (330 ft) (inferred by NRC staff)
Czarnecki, 1985	YM (regional groundwater model)	< 130 m (426 ft)

This status report has focused on the effects of past climate change on the regional water table and what may reasonably be expected in the future. Wisconsin-age water-table rise occurred under natural conditions uninfluenced by humans. Future human activities will undoubtedly have a major influence on the regional flow system. The most recent water-supply forecast for southern Nye County (Nevada) is presented by Buqo (1997). Despite access to Lake Mead, the city of Las Vegas is experiencing water supply problems. Las Vegas continues to be one of the fastest growing cities in the United States. WRMI (1992) reported that, even if responsible water conservation is imposed, all available water resources would be fully used by the year 2006, and after that time additional water sources would be needed. Groundwater is the most likely new source of water supplies for Las Vegas Valley, and given the very low rates of groundwater recharge in southern Nevada it will be

necessary to adopt a regional approach to groundwater development to prevent local potentiometric drawdowns from becoming extreme. This means that a large region will have to be developed for groundwater supplies, including areas to the north and west. The YM site and the Amargosa Desert occur in this extended region northwest of Las Vegas Valley.

Tectonic and volcanic events could also possibly influence the regional water table. These mechanisms, along with future human activities, will be discussed in some detail in an IRSR dedicated to saturated zone topics. DOE may consider that human activities could cause future water-table rise to be less than occurred in the past. However, DOE's safety analysis should assume that the climate-related component of future water-table rise will be at least as great as has occurred in the past. It is DOE's responsibility to reasonably demonstrate that future water-table conditions are consistent with postulated dose scenarios, which may include groundwater pumping, irrigation, and other activities.

5.0 STATUS OF SUBISSUE RESOLUTION AT THE STAFF LEVEL

The staff has identified no open items solely related to future climate change and associated hydrologic effects. Accordingly, the staff has no further questions at this time on methods to estimate future climate variability, or regarding methods to estimate hydrologic effects of climate change (e.g., future precipitation and water-table rise).

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Appendix A

Draft Figure Illustrating Elements of the NRC Staff's Total System Performance Assessment

DRAFT

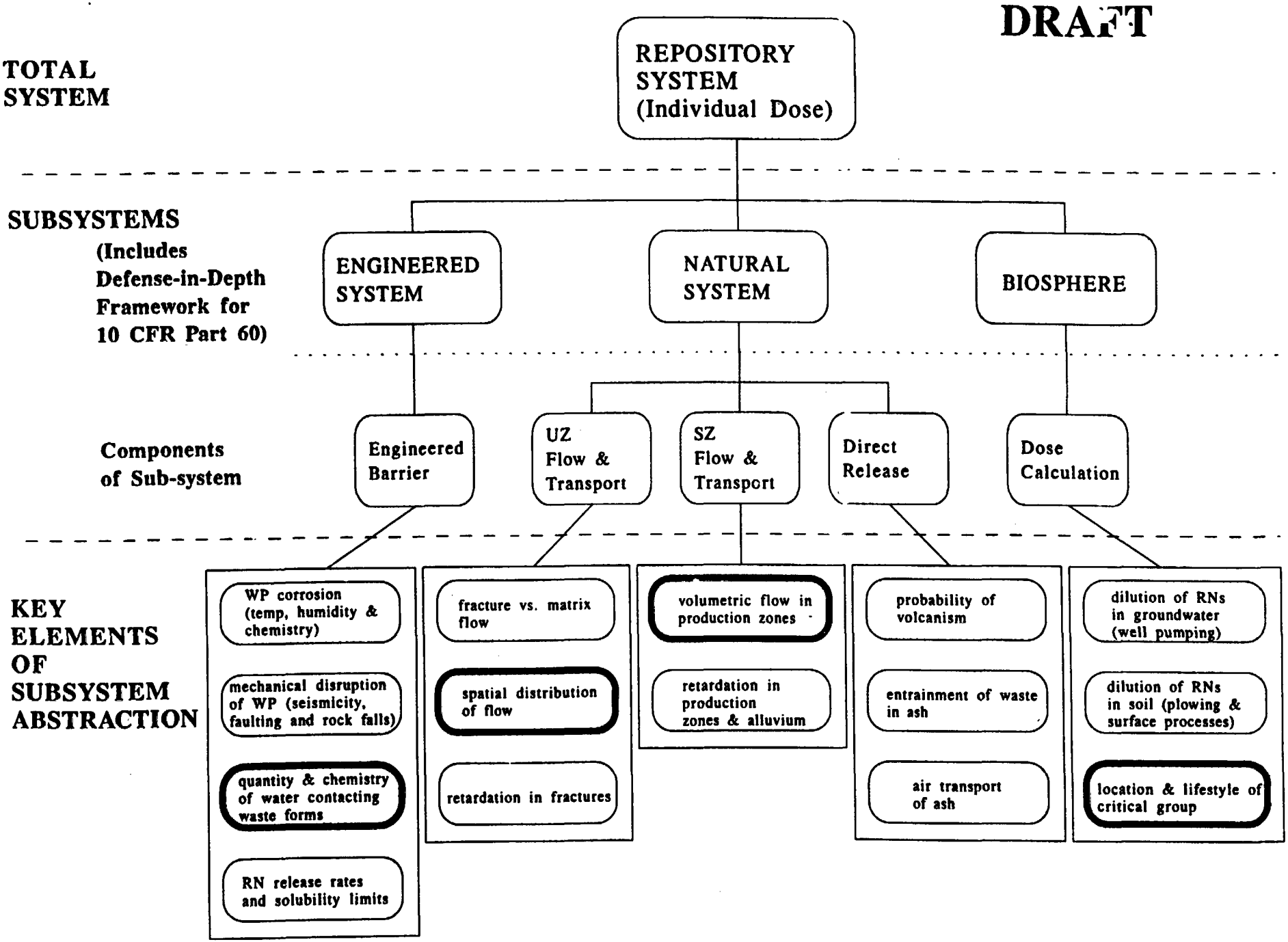

Figure A-1. Flowdown diagram for total system performance assessment. The subissue of "Climate Change" provides direct input to the highlighted key elements.