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Study Plan for
Study 8.3.1.5.1.6

Characterization of Future Regional Climate and Environments

U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Washington, DC 20585

Prepared by
Sandia National Laboratories

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YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT
STUDY PLAN APPROVAL FORM

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STUDY PLAN FOR SITE CHARACTERIZATION PLAN STUDY 8.3.1.5.1.6 CHARACTERIZATION OF FUTURE REGIONAL CLIMATE AND ENVIRONMENTS

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Abstract

The purpose of Site Characterization Plan Study 8.3.1.5.1.6 is to generate the future climate information needed to determine site suitability and regulatory compliance for the potential high-level nuclear waste repository at Yucca Mountain, Nevada. The objective of the study is to evaluate parameters relevant to repository performance for reasonably probable local climate scenarios for the Yucca Mountain area that are most challenging to repository integrity over the period of concern. The approach is to develop reasonable climate scenarios which bound the threat to repository integrity over the next 100,000 yr, rather than to attempt to predict actual future Yucca Mountain climate. Numerical climate model analyses in combination with analyses to extend and transform the numerical model results in both spatial and temporal regimes are planned to provide the most meaningful information for use in support of system performance assessments. This study draws upon the technology and results being developed through the large, ongoing worldwide effort to understand climate processes and climate change impacts.

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PREFACE

The Nuclear Waste Policy Act of 1982 established deep geological repositories as the primary method for disposal of high-level radioactive waste and spent nuclear fuel. The Nuclear Waste Policy Amendment Act of 1987 directed the U.S. Department of Energy (DOE) to characterize only Yucca Mountain, Nevada as a candidate site for the first geologic repository for high-level radioactive waste. The Act as amended also named three major agencies to carry out its provisions: the DOE, the U.S. Nuclear Regulatory Commission (NRC), and the U.S. Environmental Protection Agency (EPA). The EPA promulgated environmental standards in Title 40, Code of Federal Regulations (CFR), Part 191. Regulations for licensing any civilian radioactive waste repository were issued by the NRC in 10 CFR Part 60; these regulations incorporate the EPA's standards. Based on these regulations, the DOE developed guidelines for evaluation and selection of repository sites in 10 CFR Part 960. The purpose of these regulatory requirements is to ensure that any mined geologic disposal system constructed will contain and isolate high-level radioactive waste without adverse effects to public health and safety for at least 100,000 yr.

In compliance with the directive from the U.S. Congress, the DOE developed a Site Characterization Plan (SCP) that describes the activities required to collect the necessary information related to geology, geohydrology, geochemistry, geoengineering, hydrology, climate, and meteorology (collectively referred to as geologic information) to adequately characterize the Yucca Mountain site (DOE, 1988). This information is to be used to evaluate the candidate site for suitability and regulatory compliance.

Compliance-related issues were developed into an issues hierarchy that served as a basic organizing tool for the SCP. Specific information needs have been identified by ascertaining what information is required to resolve the listed issues, and the overall site characterization program was developed to address the information needs identified in the SCP.

Section 8.3.1.5 of the SCP describes the hierarchy of investigations, studies, activities, and tasks within the climate program to provide information on past, present, and future climate conditions needed to estimate the effect of future climate on hydrology. The subject study, Characterization of Future Regional Climate and Environments (SCP 8.3.1.5.1.6), is one of six studies within the Future Climate Investigation (8.3.1.5.1). The six studies are:

- 8.3.1.5.1.1, Characterization of Modern Regional Climate
- 8.3.1.5.1.2, Paleoclimate: Lake, Playa, and Marsh Deposits
- 8.3.1.5.1.3, Terrestrial Paleoecology Climatic Implications
- 8.3.1.5.1.4, Quaternary Regional Paleoenvironment
- 8.3.1.5.1.5, Paleoclimate/Paleoenvironment Synthesis
- 8.3.1.5.1.6, Future Regional Climate and Environments

In the first study (8.3.1.5.1.1), data will be collected to characterize both relevant meteorological parameter averages and spatial and temporal variations in the present regional climate. (Note that much of the scope of Study 8.3.1.5.1.1 is planned to be transferred to Study 8.3.1.12.1.1, "Characterization of Modern Regional Meteorological Conditions.) The second study (8.3.1.5.1.2) makes climatic inferences from paleolake, playa, and marsh sediments, and will draw upon the paleontology, stratigraphy, sedimentology, and geochemistry of these deposits. The third study (8.3.1.5.1.3) examines the climatic implications of terrestrial paleoecology based on evidence from pack rat midden macrofossils, palynology (spores and pollen), and vegetation-climate relations. The fourth study (8.3.1.5.1.4) of the paleoenvironment of the Yucca Mountain site involves research into rates and conditions of soil development, distribution and geomorphology of surficial deposits, and the eolian history of the region. The paleoclimate history (from studies 8.3.1.5.1.1 through 8.3.1.5.1.3) and the paleoenvironment history (from study 8.3.1.5.1.4) will crosscheck and complement each other and will be combined in the fifth study (8.3.1.5.1.5) to create a final paleoclimate-paleoenvironment synthesis, an integrated chronology, and a description of paleoclimate episodes at Yucca Mountain and environs. The integrated chronology and paleoclimate description will serve as a resource for SCP study 8.3.1.5.1.6, which focuses on potential climate characteristics for the Yucca Mountain area over the next 10,000 to 100,000 years.

In the interval since the SCP was published, climate research itself has undergone dramatic political, scientific, and technological development. Most of the impetus for these developments has arisen from concerns about the impacts of the changing composition of the atmosphere, due in part to the combustion of fossil fuels and the emission of other long-lived greenhouse gases. The World Climate Research Programme (WCRP) organized by the International Council of Scientific Unions and the World Meteorological Organization, the U.S. Global Change Research Program (USGCRP), and the landmark publications of the Intergovernmental Panel on Climate Change (IPCC) are indicative of the attention now being given to global climate (Houghton, 1984; WCRP, 1986-1993; CEES, 1993; IPCC, 1990 and 1992). As a participant in the USGCRP, the DOE, along with other federal agencies, has developed programs which are expected to better define or bound the major uncertainties associated with the issue of climate change. The DOE programs include the Atmospheric Radiation Measurement (ARM) Program, the Computer Hardware, Advanced Mathematics and Model Physics (CHAMMP) Program, the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and others (DOE, 1992). The National Aeronautics and Space Administration (NASA), through its Mission to Planet Earth and Earth Observing System, and the National Oceanic and Atmospheric Administration (NOAA), through its Climate and Global Change Program, are joined by the National Science Foundation (NSF), the U.S. Department of Defense, the U.S. Department of the Interior, the EPA, the U.S. Department of Agriculture, the U.S. Department of Health and Human Services, the Smithsonian Institution, and the Tennessee Valley Authority in participating in the USGCRP.

Many other countries have substantial climate change programs as well, principally as part of WCRP constituent activities, including the Global Energy and Water Cycle Experiment (GEWEX) (WCRP, 1989), the Tropical Ocean/Global Atmosphere (TOGA) (WCRP, 1990), the World Ocean Circulation Experiment (WOCE) (WCRP, 1988), and Arctic Climate System Study (ACSYS) (WCRP, 1993) programs. The net result is that the rate of progress in understanding and modeling climate processes has accelerated enormously since publication of the SCP. Although this greatly enhanced level of research does not focus on the Yucca Mountain (Site Characterization) Project (YMP), there are significant implications for the YMP future climate activity.

Climate-related efforts in support of other SCP studies within Section 8.3.1.5 and scoping work supporting the subject study, 8.3.1.5.1.6 that specifically focus on Yucca Mountain, have also been performed and can be used to guide the activities planned for the subject study. The result of the efforts both in the general area of climate research and research specific to Yucca Mountain is that modifications in the details of the plan put forward in the SCP are now needed. This document provides an updated and detailed description of the activities currently planned for SCP Study 8.3.1.5.1.6. However, in view of the rapid development of climate research, it is anticipated that certain activities in this area will be performed in an iterative manner, drawing upon and incorporating ongoing developments in the understanding of climate processes and climate modeling as that understanding evolves.

ACRONYM LIST

ACSYS	Arctic Climate System Study
AMIP	Atmospheric Model Intercomparison Project
ARM	Atmospheric Radiation Measurement (DOE Program)
BP	(years) Before Present
CEES	Committee on Earth and Environmental Sciences
CCM	Community Climate Model
CFR	Code of Federal Regulations
CHAMMP	Computer Hardware, Advanced Mathematics and Model Physics (DOE Program)
CLIMAP	Climate: Long-range Investigation Mapping and Prediction
COHMAP	Cooperative Holocene Mapping Project
DOE	United States Department of Energy
ECMWF	European Centre for Medium-Range Weather Forecasts
EPA	United States Environmental Protection Agency
GCM	General Circulation (or Global Climate) Model
GENESIS	Global Environmental and Ecological Simulation of Interactive Systems
GEWEX	Global Energy and Water Cycle Experiment
GRIP	Greenland Ice Core Project
IPCC	Intergovernmental Panel on Climate Change
MM4	Mesoscale Model Version 4
My	Million years
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NRC	United States Nuclear Regulatory Commission
NSF	National Science Foundation
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PMIP	Paleoclimate Model Intercomparison Project
RCM	Radiative-Convective Model
RegCM	Regional Climate Model
RLCS	Reference Local Climate Scenario
SCP	Site Characterization Plan
SNL	Sandia National Laboratories
SST	Sea Surface Temperature
TOGA	Tropical Ocean/Global Atmosphere (Project)
USGCRP	United States Global Change Research Program
USGS	United States Geological Survey
WCRP	World Climate Research Programme
WOCE	World Ocean Circulation Experiment
YMP	Yucca Mountain (Site Characterization) Project

1.0 STUDY PURPOSE AND OBJECTIVE

The purpose of SCP Study 8.3.1.5.1.6 is to generate the future climate information needed to support the determination of site suitability and regulatory compliance for the Yucca Mountain site.

The SCP states that the objective of this study is to estimate values of climatic parameters for the Yucca Mountain area over the next 100,000 yr, with special emphasis on the next 10,000 yr. This should not be interpreted as implying that credible climate forecasts for the next 100,000 yr can be made on the basis of current understanding. In view of the substantial uncertainties associated with global climate and especially the additional uncertainties arising from anthropogenic climate effects, the objective is restated here in modified form: *to evaluate the parameters relevant to repository performance for the local climate scenarios most challenging to repository integrity and reasonably probable for the Yucca Mountain candidate area over the period of concern.*

In this context, *to evaluate* means to determine the values. The term *parameters relevant to repository performance* means the specific information needed to model hydrology, and hence, to model repository performance. The implication is that it is not enough to provide climate scenarios consisting of generic descriptions of climate as a function of time without reference to the parameters actually needed by hydrology modelers. Rather, there are quite specific information needs beyond the usual focus of climate studies.

The parameters of interest here include, but may not be limited to, precipitation (rain and snow separately), precipitation rate, wind speed and direction, surface insolation, surface albedo, surface temperature, near-surface air temperature and relative humidity, surface soil moisture, surface pressure, evapotranspiration potential, and actual evapotranspiration rate. These are the time-dependent parameters that, together with site-specific surface and subsurface geological characteristics, determine surface and subsurface hydrology, e.g., surface runoff, water storage as a function of depth, infiltration as a function of depth, and other related parameters.

As used in the restated objective, the term *most challenging to repository integrity* means most likely to stress the integrity of the potential repository with regard to compliance with DOE, NRC, and EPA regulatory requirements.

The adjective *local* points to the fact that the information needed is that required to model the hydrology specifically at and near the proposed repository. Repository performance modelers need scenarios for infiltration (unsaturated zone water fluxes) at the proposed repository depth over the entire area of the candidate site. These fluxes are influenced by the surface hydrology over a somewhat broader area, but an area significantly smaller than is usually considered regional in a meteorological or climatological context. The local area in this context is the area that influences water fluxes and the location of saturated zones in the vicinity of the candidate repository site. Thus global and even regional climate scenarios are only of derivative interest. They strongly influence the local climate scenario, but are not themselves the focus of ultimate interest.

The term *climate scenario* refers implicitly to the time dependence of climate. It is not enough to identify steady-state climates which maximally challenge repository integrity, or to estimate the corresponding fixed average parameter values. Over the time scales of concern, steady-state climate is not a useful concept. Research by the Flints, Hevesi, and others (Flint et al., 1993; Hevesi and Flint, 1993; Long and Childs, 1993) provides evidence that time dependence cannot be ignored in modeling hydrology for performance assessment. Furthermore, the time scales of importance cover several orders of magnitude. Surface and very-near-surface water fluxes are dominated by processes which have time constants ranging from fractions of an hour to years. Fluxes at depths from tens to hundreds of meters have time constants ranging from a fraction of a millennium to tens of millennia or even longer. However, because the surficial fluxes feed the deep fluxes, it is necessary to take all of these time scales into account in specifying the local climate scenarios which are the focus of this study.

The term *reasonably probable* is perhaps most ambiguous. It means, considering what is known about global, regional, and Yucca Mountain present climate and paleoclimates, and what can be inferred from climate modeling studies of potential future climates, that the local climate scenarios identified as reasonably probable over the period of concern are credible to knowledgeable climatologists. Ultimately, the determination depends upon expert judgement. It is possible to be more quantitative in defining what one means by reasonably probable under the assumption that, in the future, the climate system will behave as it has in the past. However, in the presence of anthropogenic effects, that is a questionable assumption.

The term *period of concern* means 100,000 yr, although, depending upon precisely how future regulations are written, it is possible that the period of concern could become even longer.

In effect, the objective of this study is to develop Reference Local Climate Scenarios (RLCSs) for the Yucca Mountain site that include time-dependent values for all parameters influencing the degree climatic conditions can stress a potential repository. To develop a RLCS implies that a RLCS is not the direct output of a climate model, but rather the product of climatologists making use of climate model results together with all other information available to them. The word *scenarios* is plural to take into account that there may be more than one general type of scenario which poses a significant challenge to repository integrity, and to accommodate the fact that performance modelers want information not only on the most challenging scenarios, but also on scenarios that are more (or less) probable.

Because of the inherent inability to accurately predict future climatic events, the RLCS approach has been devised as a means to address the question of the potential impacts of future climate change on performance. However, on the basis of information from all available sources, reasonable constraints can be placed on what is probable within a specified time interval, be it 100 or 100,000 yr. In that regard, planning for a high-level nuclear waste repository is similar to planning for any other major public facility. The time horizon is just much longer.

2.0 SCOPE OF WORK

2.1 Background

The earth has existed in more or less its present planetary form for approximately four billion years. Over that time, many fundamental changes in the earth system and its climate have occurred (Crowley and North, 1991). Continental drift has altered the distribution of land and sea on the earth's surface with profound effects on ocean currents and climate. Continental drift and plate tectonic interactions have also raised mountain ranges that strongly influence local and regional climate. The rise of life on earth has fundamentally modified the composition of the earth's atmosphere. Without life, there would be little free oxygen, and the concentrations of carbon dioxide and other greenhouse gases would be markedly different from present values. Even the energy output of the sun appears to have slowly changed and the distribution of solar insolation on the surface of the earth is also continually changing, but in a predictable way due to orbital perturbations caused by the other planets. In short, the paleorecord of the earth reveals a highly dynamic, interactive, and perhaps technically chaotic climate system (Lorenz, 1991).

During approximately the last two million years (the Pleistocene; see Figure 1), the earth has been undergoing glacial/interglacial cycles. These cycles have been shown to correlate well with the variations in the orbital parameters of the earth (Hays et al., 1976; Milankovitch, 1941). During the last 700,000 yr, glaciations have alternated with warmer interglacials with a period of ~100,000 yr (Crowley and North, 1991). One hundred thousand years corresponds to one of the periods associated with orbital perturbations. Interglacials have typically lasted ~20,000 yr. During glacials, ice volume has gradually built up, and then, over a period of a few thousand years, precipitously declined to interglacial values. During the buildup, there is evidence that global ice volume is modulated by the other known orbital perturbation periods. The earth is currently in the midst of an interglacial that began ~14,000 BP yr before present (BP).

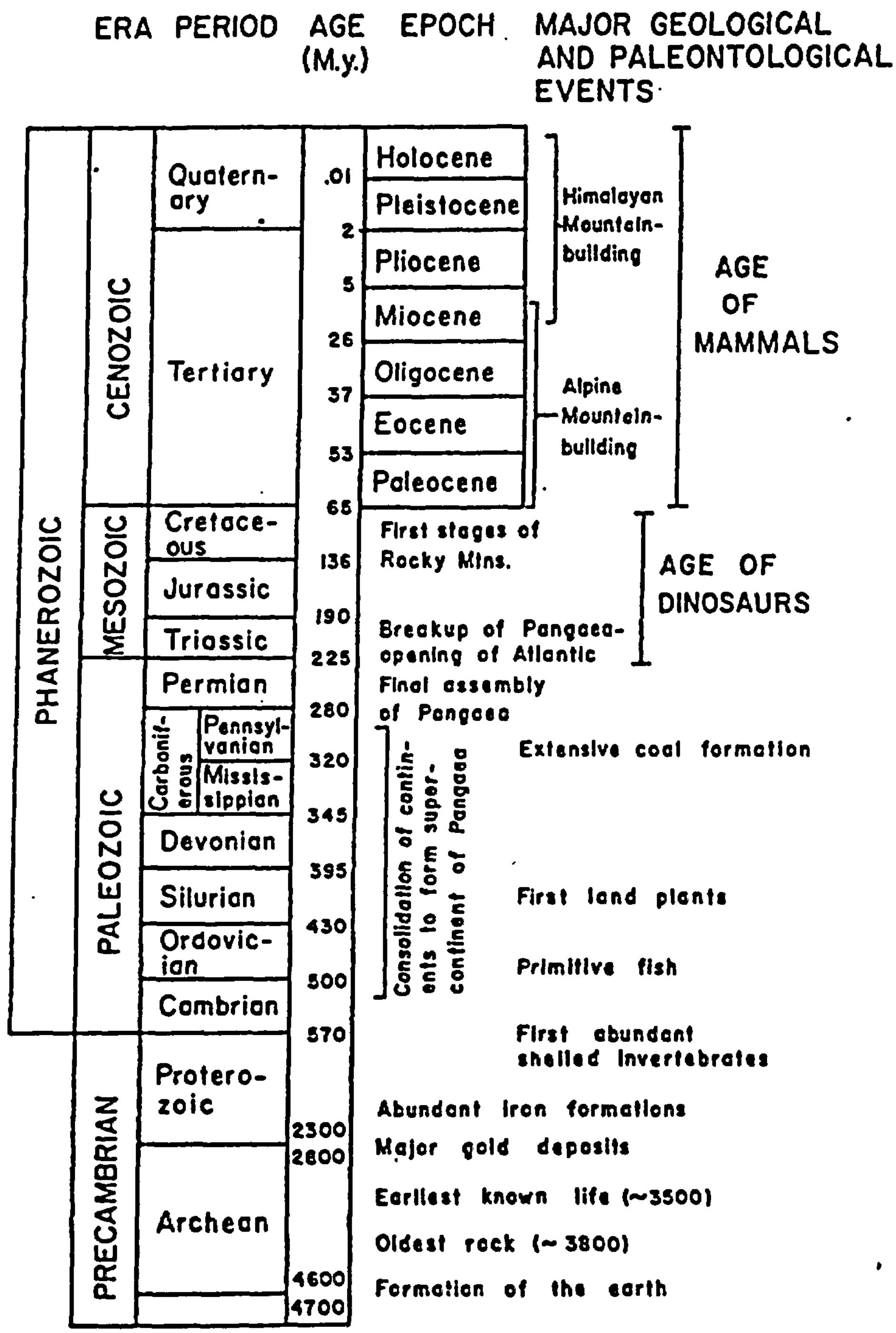


Figure 1. Geological and Paleontological Chronology
(Crowley and North, 1991)

The present interglacial epoch, called the Holocene, appears to have had a much more stable climate than at least the previous two interglacials (GRIP Members, 1993). During glacial periods, the earth has been on average several degrees Celsius cooler than at present and most of the earth has been drier. However, during at least the most recent glacial, the Yucca Mountain region, while cooler, has also been wetter than at present (Spaulding, 1985). This anomaly is believed to have been caused by a southward shift of the jet stream around the southern end of the continental ice sheets. Such a shift would have brought down the storm track now over the Pacific Northwest to over what is now the southwestern United States.

The previous interglacial, between 135,000 BP and 115,000 BP, contained several periods for which there is evidence of sudden and sustained return to glacial conditions (for hundreds to thousands of years), at least in the North Atlantic (GRIP Members, 1993). On a global scale, it is unknown how widespread and intense these returns to glacial conditions were.

Over the last century or two, humanity has become a significant factor in influencing the earth's climate in at least two ways. First, human activities have begun to directly affect the composition of the earth's atmosphere through the burning of fossil fuels (with the resulting release of carbon dioxide to the atmosphere) and through the production and release of other long-lived greenhouse gases. Second, human activities have changed the character of the earth's surface on a massive scale. The inexorable conversion of wild lands to agriculture to feed the world's rapidly growing population is the principal driver. These surface modifications have affected climate by changing surface albedo, surface roughness, and fluxes of sensible and latent heat (water) between the surface and the atmosphere, as well as by reducing fluxes of carbon dioxide to the surface (reduced net biomass production). The anticipated net effect of these changes is global warming (IPCC, 1990 and 1992).

There is evidence that the interglacial that began 135,000 BP was ~2°C warmer on average than the present interglacial. Concern has been expressed that these warmer conditions may be associated with the much greater climatic instability observed for that period in the Greenland ice core record and that the anthropogenic global warming now underway might precipitate similar instability (GRIP Members, 1993).

The global-scale changes which humanity has wrought make it a questionable proposition to simply extrapolate from the past to the future. Nevertheless, it is sometimes assumed that when fossil fuels have been exhausted (within the next thousand years or so), the climate system will slowly return to its previous state. However, in light of the breadth of human influence and the uncertainties associated with climate even in the absence of such influence, that assumption is questionable. In spite of this fact, information about the present and past climates provides a valuable tool for developing constructs of an uncertain future. Until climatologists have a reasonable understanding of the present and the past, they can have little confidence that they understand the future.

Because of the highly dynamic and possibly chaotic nature of the climate system, it might appear at first glance that satisfying the objectives of this study will require an extraordinarily challenging effort. Such is not the case. Even so-called chaotic systems are subject to limits. The objective here is to determine the limits applicable to a time period that is short relative to the characteristic times associated with some of the most important climate-influencing processes. Judging from the paleorecord, the spatial distribution of land masses on the surface of the earth, altitude profiles of the continents, and ocean depths will not significantly change within the next 100,000 yr, particularly in comparison to inherent model uncertainty and other limitations. Changes in these characteristics of the earth have been responsible for fundamental changes in global climate (e.g., subtropical conditions in the Arctic) over tens of millions to hundreds of millions of years. Defensible bounds can also be placed on how much the composition of the earth's atmosphere is likely to change over the next 100,000 yr. From the paleorecord and knowledge of the physics involved, defensible estimates of the upper and lower limits of the distribution of ice sheets, as well as of the distribution of sea surface temperatures (SSTs) can also be made. Over the period of interest, defensible limits can be placed on changes in the sun's energy output and the distribution of solar insolation over the surface of the earth. Thus, although from a human perspective 100,000 yr is a long time, from a geological and climatological perspective, it is a period of modest length.

Global climate has experienced great swings since the formation of the earth, but the range of credible climate scenarios over the next 100,000 yr is considerably narrower. Taking into account the limits which can be placed on global climate states over the next 100,000 yr, numerical models can tell us what those global limits mean for the potential repository site at Yucca Mountain. The effort to understand the limits on credible climate change at the site over the period of concern is essential. In the absence of such understanding, decision-makers lack the information needed to make rational choices about nuclear waste isolation.

2.2 Overview

The SCP lists the constituent activities of 8.3.1.5.1.6 as:

- 8.3.1.5.1.6.1, Global Climate Modeling
- 8.3.1.5.1.6.2, Regional Climate Modeling
- 8.3.1.5.1.6.3, Linked Global-Regional Climate Modeling
- 8.3.1.5.1.6.4, Empirical Climate Modeling

At the time the SCP was written, there was substantial uncertainty about the feasibility of linking (nesting) a Regional Climate Model (RegCM). (RCM is not used here instead because, to climate modelers, RCM means Radiative-Convective Model within a General Circulation [or Global Climate] Model [GCM].) In the interim, nesting RegCMs within GCMs has been successfully accomplished (Giorgi et al., 1992). Hence, separate activities for Regional Climate Modeling and Linked Global-Regional Climate Modeling are no longer needed and only the latter is retained (as 8.3.1.5.1.6.2). Empirical Climate Modeling has been eliminated as such, but a similar functionality has been preserved in 8.3.1.5.1.6.3, Site-Specific Model Output Adjustment, and in 8.3.1.5.1.6.4, Future Climate Synthesis. The result is a modified list of constituent activities:

- 8.3.1.5.1.6.1, Global Climate Modeling
- 8.3.1.5.1.6.2, Nested Global-Regional Climate Modeling
- 8.3.1.5.1.6.3, Site-Specific Model Output Adjustment
- 8.3.1.5.1.6.4, Future Climate Synthesis

At present, no existing GCM can credibly predict future climate over the next 100,000 yr solely on the basis of the initial (present climate) conditions. This is true even in the absence of inherently unpredictable future human activities. However, given four additional global boundary condition sets, a number of GCMs appear to predict reasonably well how those global boundary conditions translate into global climate. Those additional boundary conditions include: (1) solar insolation at the top of the atmosphere as a function of season and latitude, (2) ice sheet distribution, (3) SST distribution, and (4) greenhouse gas concentration.

Of these four global boundary condition sets, with the exception of the first (solar insolation) and in the absence of human intervention, the remaining conditions are produced by the earth's climate system itself. However, existing global models are not sufficiently sophisticated and complete in their description of climate system processes to permit those conditions to be accurately predicted over the next 100,000 yr. It is clear, for instance, that the climate system involves the coupled interactions of the atmosphere, the hydrosphere, the cryosphere, the lithosphere, and the biosphere. Available models have not mastered the problem of coupling even the atmosphere and the ocean in a fully interactive manner, much less all of these spheres simultaneously. Significant uncertainties exist in the appropriate description of relevant natural processes as well. Nevertheless, the degree of success experienced in predicting global climate given the four global boundary condition sets is encouraging, and suggests an approach to the problem of estimating limits on future climate conditions in the Yucca Mountain area over the next 100,000 yr.

Present climate and paleoclimate studies allow reasonable estimates of how global boundary conditions varied over the last glacial cycle or two (CLIMAP, 1981; COHMAP, 1988; Peltier, 1993). Those studies together with present climate, paleoclimate, and future climate modeling efforts (Crowley and North, 1991; Boer et al., 1992), have provided qualitative insight into how conditions in the Yucca Mountain region have been and are likely to be influenced by the global boundary conditions. To render that insight quantitative, one needs to run one or more carefully chosen and validated GCMs for selected sets of global boundary conditions. The sets are selected to emphasize conditions likely to favor enhanced infiltration at Yucca Mountain, which is of greatest importance to site suitability and regulatory compliance concerns. Effectively, one needs to do the sensitivity study embedded in the first activity, 8.3.1.5.1.6.1.

Present-day GCMs, however, have grossly insufficient resolution to make predictions specifically for the Yucca Mountain area. Typical resolution is of order 400 km to 500 km (Figure 2), although a few runs have been made at resolutions as high as 100 km. Over the last several years, progress has been made at overcoming the resolution limitations of GCMs by "nesting" a RegCM within a GCM, which produces boundary conditions for the RegCM (Giorgi et al., 1992). Nested GCM-RegCM modeling of the Yucca Mountain regional climate is the subject of the second activity, 8.3.1.5.1.6.2. Resolution of the RegCM can be varied, but the finer the resolution, the higher the cost of running the RegCM for a specified simulation interval. Given present computational costs, this consideration sets the affordable resolution for multi-year nested GCM-RegCM production runs to ~50 km (Figure 3). Nor is cost the only limitation. Numerical stability and fundamental applicability of the algorithms set limits on RegCM resolution in the vicinity of 10 km x 10 km (depending upon the specific RegCM). This is still inadequate to simulate the relevant climate conditions over the area of interest, a problem which is addressed in the third activity, 8.3.1.5.1.6.3. On the basis of experimental data and/or sensitivity studies of the effect of resolution on RegCM results, it is possible to determine defensible correction algorithms to the RegCM output to predict climatic parameters in the area of interest for the selected conditions (Wigley et al., 1990; Karl et al., 1990). Alternately, another level of model nesting may prove feasible.

The results of the first two activities will provide predicted climate descriptions specific to Yucca Mountain for selected global boundary conditions, but do not indicate which of the credible global climates result in the local conditions most challenging to repository integrity. Further, these activities do not specify the degree of uncertainty associated with the nested GCM-RegCM results as adjusted to the Yucca Mountain area or provide the time dependence of the relevant climatic parameters over the next 100,000 yr. The third activity (8.3.1.5.1.6.3) is thus intended to develop methods to analyze and transform the numerical modeling results into more useful spatial and temporal information for the specific site.

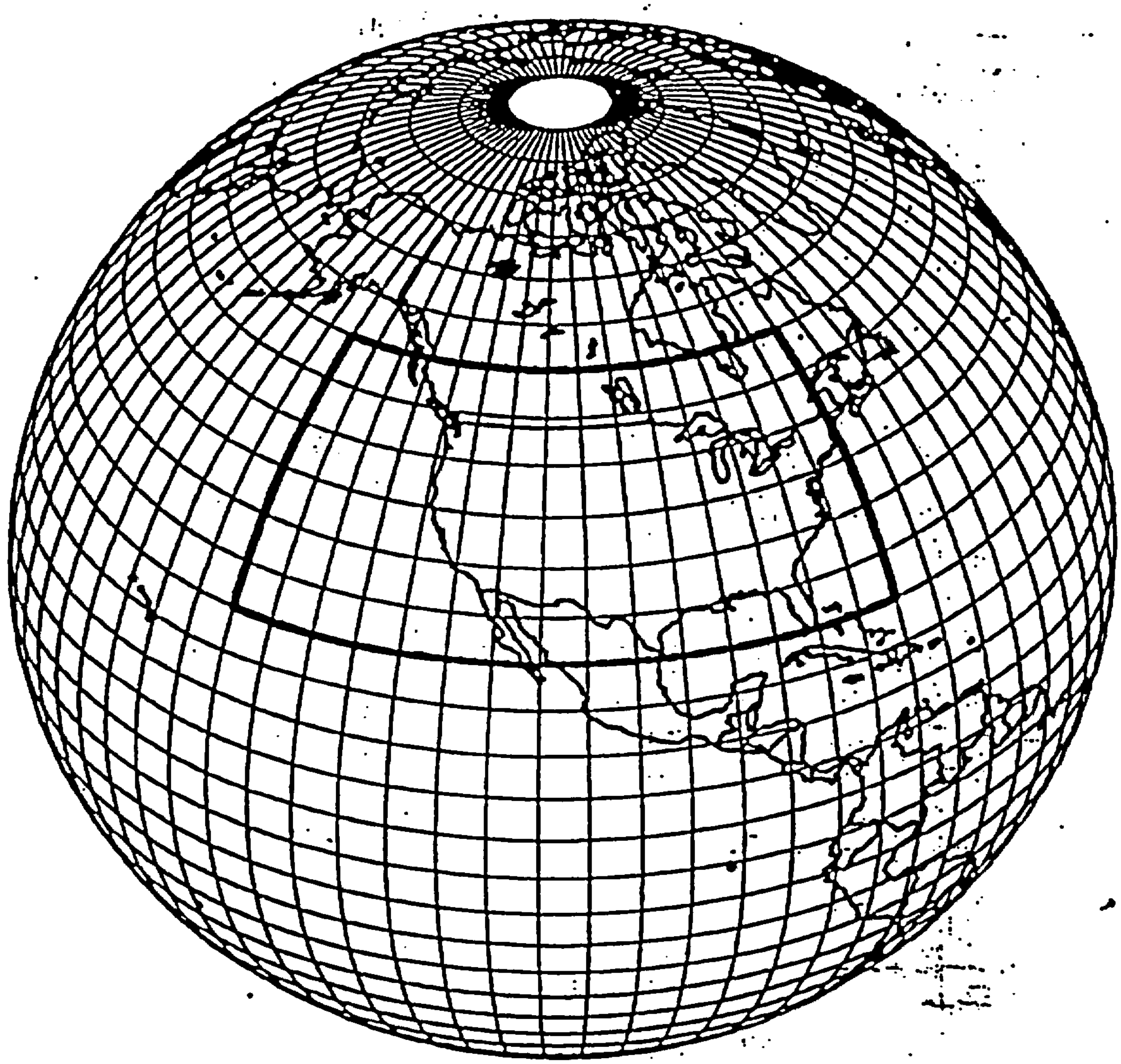


Figure 2. Representative Global Climate Model Grid (5 Degree Latitude-Longitude Resolution)

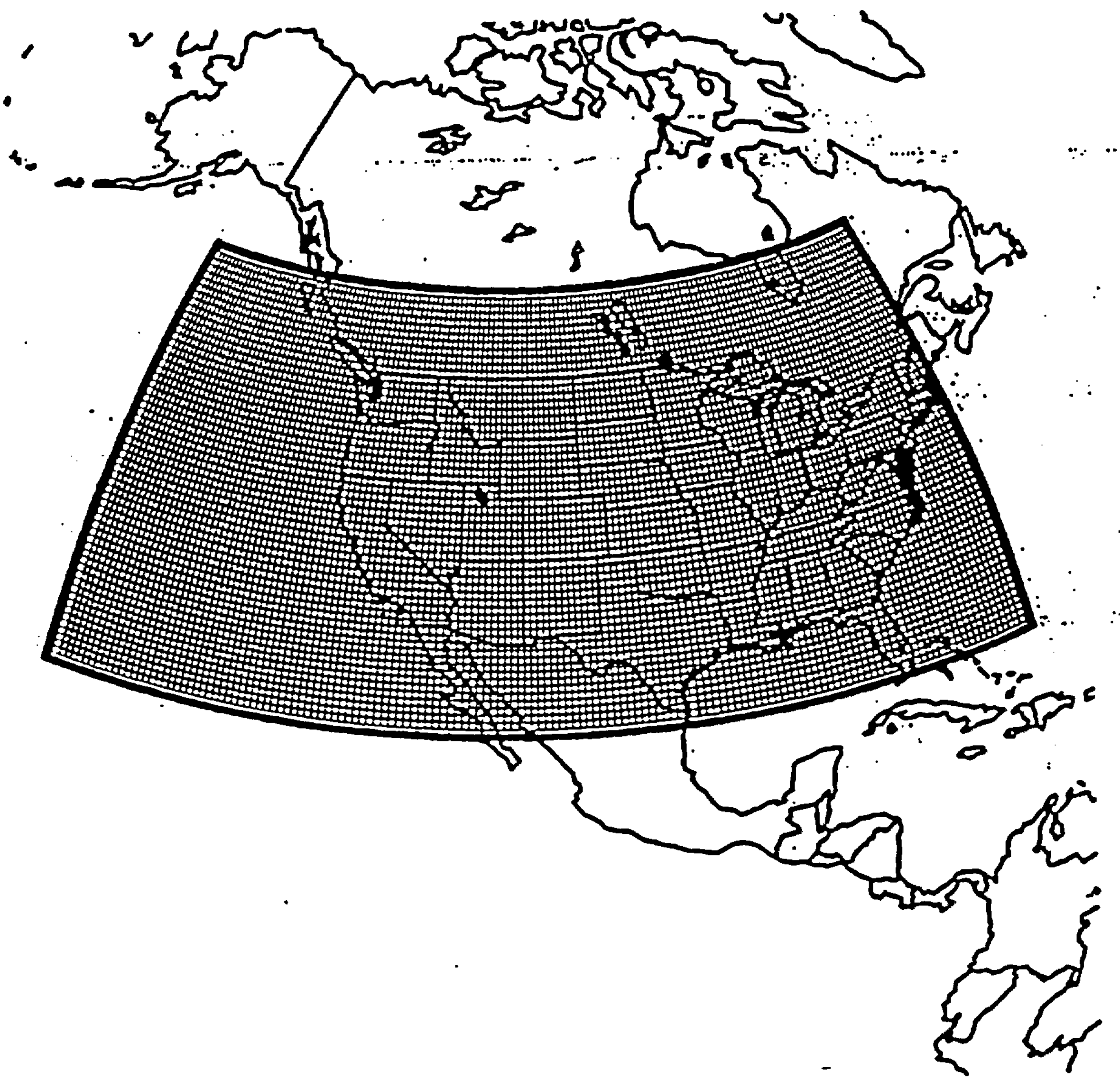


Figure 3. Representative Regional Climate Model Grid (0.5 Degree Latitude-Longitude Resolution)

When the numerical modeling and model analysis activities described here are complete, an additional step remains: defining a subset of local climate scenarios for the Yucca Mountain area, each of which is referred to as a Reference Local Climate Scenario (RLCS) and designed for use by performance modelers in characterizing climate threats to repository integrity. On the basis of the numerical modeling and the model analysis results, together with the integrated paleoclimate-paleoenvironmental chronology from activity 8.3.1.5.1.5, all available information is synthesized in the final activity (8.3.1.5.1.6.4) of this study and used to develop RLCSs.

The process of developing RLCSs for use in analyzing future hydrology, and ultimately, future repository performance, relies heavily upon expert opinion. In the SCP, two expert panels are mentioned. One panel would focus upon global modeling and the other panel would focus upon regional modeling. With the more integrated approach presented here, there would be no benefit to be gained from dividing the consultants into two separate groups. To provide additional assurance regarding the soundness and defensibility of project approaches, interpretations, and conclusions, nationally and internationally respected climatologists, including both paleoclimate experts and numerical modelers, will be consulted and their opinions documented.

2.3 Global Climate Modeling, Activity 8.3.1.5.1.6.1

The SCP lists the following objectives for this activity:

1. Identify and estimate factors controlling global climate.
   a. Develop a sequence of "snapshots" of possible climate scenarios at intervals of up to 1,000 yr over the next 10,000 yr.
   b. Develop a set of anticipated global climate scenarios for the next 100,000 yr.

2. Compute the configuration and extent of ice sheets for regular intervals over the next 100,000 yr to determine the effects of ice volume changes upon the climatic system.

3. Provide boundary conditions, including precipitation, temperature, cloud cover, evapotranspiration, and wind velocity for regional climate models through the use of GCMs.

At the time the SCP was written, the computational costs of running GCMs were high, indicating that much weight would need to be placed on analyses based on the use of a hierarchy of simpler (and cheaper) models. Only limited use could be made of the expensive high-resolution GCMs. The lower costs associated with the simpler models permits many runs to be made, but both the resolution available and the level of confidence that can be invested in the results limits their utility. In the interim, both computer and climate model technology have advanced greatly. As computer technology has advanced, the cost of running GCMs has been coming down monotonically, making it feasible to use GCMs more extensively. There is also a greater appreciation of the reasons why GCMs are preferred. Hence, in this study plan, there has been a shift away from the simpler models toward greater reliance on GCMs.

These developments make it desirable to modify the statement of the objective(s) for the Global Climate Modeling activity, even though the planned effort is not fundamentally changed. A succinct statement of the objective of the activity is *to use one or more carefully-chosen GCMs with selected global climate states (global boundary conditions) to produce time-dependent regional boundary conditions corresponding to those states for use in driving RegCMs.*

2.3.1 General Circulation Model Selection and Validation

There are more than 30 GCMs in use around the world (Gates, 1992). Although there are many similarities, in their present versions, the models differ significantly in both how they treat specific climate processes and in the results they produce for specified global initial and boundary conditions (Boer et al., 1992). Thus, in principle, GCM selection is a significant task in itself. In practice, the choice is restricted. Some of the models reflect old technology, and either do not include the best available parameterizations of climate processes, are computationally inefficient, or do not run on the most cost-effective computers available. Other models are designed for specific uses (e.g., long simulated-time runs that make it necessary to eliminate diurnal variations). Most have not been adapted to accommodate nesting with RegCMs. For the purposes of this study, several other model requirements can be specified, including a model that is: (1) available (including personnel and computing resources needed to run it); (2) fully GCM-based, with the capability for incorporation of predicted SSTs, sea ice, and up-to-date land surface processes; (3) well-established and documented in the open literature; and (4) has a background of use for paleoclimate studies (as an indicator of robustness for large variations in boundary conditions).

Taking these considerations into account, a tentative GCM selection has been made. For this study, a version of the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM), the Global Environmental and Ecological Simulation of Interactive Systems (GENESIS) model, is proposed to be used (Pollard and Thompson, 1993). Part of the selection task is to document why this is an appropriate selection and to consider whether any other GCMs might also be appropriate. The matter of model selection, however, does not end there. This GCM, like most, is continually being improved. In order to carry out the study plan described herein, at some point it is necessary to choose the specific version(s) of GENESIS to be used and document the reasons for that choice.

Model validation is the next task to be considered. Before a GCM can be used to evaluate future climatic conditions, it must accurately simulate the present climate, given present global boundary conditions. This will be done for GENESIS through the Atmospheric Model Intercomparison Project (AMIP), part of the Program for Climate Model Diagnosis and Intercomparison (DOE, 1992). A GCM should also be demonstrated to simulate past climates to within the uncertainty that past global boundary conditions and climates are known. For GENESIS, this will be done through the Paleoclimate Model Intercomparison Project (PMIP), also part of PCMDI.

For the present climate, validation is typically done by evaluating global indices of agreement between observed and predicted climates. This evaluation, for example, includes comparisons of monthly mean values of standard climate fields between observational data compilations and model results. Typical of the parameters evaluated in this manner are surface air temperatures and humidities, precipitation and cloud amounts, wind direction and velocity at various heights, surface snow amounts, and possibly, soil moisture and runoff. Comparisons can also be made of near surface diurnal cycles and variability. These evaluations will include both objective methods, such as comparison of root mean square differences between parameter values and more subjective methods, including the evaluation of distribution maps. The extent to which the models can be validated against observational data depends on the comprehensiveness and quality of the availabile data. These comparisons are performed for the purpose of demonstrating that model simulations predict conditions similar to that expressed by the natural climate system. One does not expect to establish in advance quantitative acceptance limits for determining a satisfactory level of agreement between model results and observational data; rather, the validation results guide the determination of the extent to which reliable interpretations and conclusions can be drawn from simulation results.

While this validation step is necessary, another step in the GCM validation for this study needs to focus on how well the selected GCM(s) reproduce the boundary conditions to be used to drive a RegCM. If a selected GCM does well when evaluated against global indices of success, but does poorly in predicting the boundary conditions which will be used to drive the RegCM, that GCM would be inappropriate for use in this study. For the GCM validation task relating to RegCM boundary conditions, gridded weather analyses from the European Centre for Medium Range Weather Forecasting will be used for comparison (Trenberth and Olson, 1988). As described in Section 2.4.2, this dataset will be used to generate boundary conditions for the validation of the stand-alone version of the RegCM. Demonstrating that the GCM adequately reproduces these conditions is an important step in the GCM validation process.

Undertaking further model refinement is the usual response by modelers to less-than-perfect model validation results. This could lead to a never-ending cycle of selection, validation, and refinement, but the primary goal of the YMP is not GCM development. Hence, expert judgement must be brought to bear to ascertain whether the validation is adequate for YMP purposes.

Expert opinion may also enter in deciding to use a model significantly different from the one tentatively selected. For instance, because of advances in massively parallel computing and ongoing research, it is conceivable that present problems with fully interactive coupled ocean-atmosphere GCMs may be overcome in time for such models to be used in this study, so that SSTs may not need to be specified as boundary conditions. Such a development would not necessarily invalidate what had been accomplished before. Rather, the likely outcome would be a modest modification of and greater confidence in the final results.

There is, however, another set of concerns underlying any dependence upon climate model results. The equations used in climate modeling are nonlinear and coupled. Such equation sets frequently exhibit regions of multiple solutions and chaotic behavior over a portion of the range of the input parameters. If such were the case here, there would be no guarantee that the output from a specific modeling exercise would be generally meaningful, in that slightly different initial or boundary conditions might produce substantially different results. Clearly, this issue needs to be addressed through sensitivity studies as well as through more fundamental consideration of the stability of the solutions to the equation sets actually utilized.

The sheer complexity of climate systems and the numerical models that simulate them makes difficult any analysis of their tendency to chaotic behavior. The two aspects of chaotic behavior of concern to the modeling program described here are sensitivity of solutions to initial conditions and long-term internally generated variability of solutions. The climatological solutions of atmospheric GCMs are not known to be sensitive to the initial state of the model except in certain extreme cases, e.g., an initially ice-covered world will remain so and not return to present conditions. Thus, sensitivity to initial conditions does not appear to present a potential problem for atmospheric GCMs. The same holds true for RegCMs because, in practice, they are simply limited domain versions of atmospheric GCMs. Some oceanic GCMs, however, do show the potential for two or more steady-state solutions for a common input forcing. This behavior arises from the dynamics of the model's thermohaline circulation and is not necessarily unrealistic. In fact, this behavior may be reflected in the actual observed climatic instability (Broecker and Denton, 1990). However, we are not proposing to use coupled GCMs in this study. Rather, we will incorporate the effects on the atmosphere of the most common oceanic GCM anomalous behavior, the cessation of North Atlantic Deep Water formation, by prescribing altered SSTs (see Section 2.3.2.f).

Long-term internally generated variability of climate model solutions is a potential problem because it is impractical to run a nested GCM/RegCM system for hundreds of simulated years or even decades. By long term, here we mean variability on the interannual to interdecadal time scale. RegCMs are not likely to produce long-term variability on their own, but are much more likely to merely respond to long-term variability in the GCM-derived boundary conditions that drive them. Long-term global climate variability that would be sensed by a RegCM would likely come from interannual changes in SSTs (e.g., El Nino events), slowly evolving sea ice or snow cover changes, or perhaps changes in terrestrial soil moisture. The latter two effects are already included in GENESIS and most other global climate models. Accurately modeling interannual and interdecadal variability of SSTs is an experimental area of research that would require an oceanic GCM at least. Again, we will mimic the effects of extreme SST scenarios that might arise from chaotic atmosphere/ocean interactions by prescribing SSTs that should result in wetter conditions at the Yucca Mountain site (see Section 2.3.2.g).

2.3.2 Selection and Development of Global Climate States for Analysis

On the basis of what is now known about paleoclimate as well as about the global warming which is believed to be underway, a preliminary list of global climate states has been proposed to be investigated by GCM/RegCM modeling in this study. This list includes those global climate states thought most likely to create wetter climatic conditions in the Yucca Mountain area, conditions which would tend to stress repository integrity. Global climate states that are not likely candidates for that distinction are also included as part of the effort to determine the sensitivity of the final predicted Yucca Mountain area climatic conditions to the assumed global climate states. The preliminary list of global climate states for GCM simulation is:

a. Present Climate
b. Intermediate Glacial
c. Full Glacial
d. Super-Glacial
e. Super-Interglacial
f. Reduced North Atlantic Deep Water

g. Extreme Greenhouse/Constrained Storm Track

Other global climate states likely to produce high levels of moisture in southern Nevada may be subsequently identified. If so, they will also be considered, and, if deemed appropriate, will be included among the global climate states to be simulated. Thus the preliminary list of global climate states to be modeled may well change over the course of the study. Note that, for sensitivity studies, the list also includes global climate states that are not considered reasonably probable over the next 100,000 yr (d, e, and g).

a. Present Climate: The present climate will be studied in great detail using the selected GCM(s) as part of the model validation effort through AMIP/PCMDI. It is included in this list for completeness.

b. Intermediate Glacial: Because the anticipated variation in ice volume for the next 100,000 yr (based on paleoclimate behavior) suggests conditions intermediate between full-glacial and interglacial, simulations will be conducted with intermediate-extent ice sheets. The choice of specific boundary conditions is dependent upon: (1) anticipated ice volume over the next 100,000 yr, and (2) analysis of paleoclimate records to determine which intermediate ice events seem most likely to produce increased wetness at Yucca Mountain. For example, Phillips et al. (1990) suggest that glaciation early in the glacial/interglacial cycle in the eastern Sierra Nevada was more extensive than later in the cycle (Richmond, 1972), a result that may implicate precipitation changes in local glacier growth (warmer SSTs early in the cycle may have caused more precipitation earlier than later). Hence, a global climate state characteristic of conditions expected shortly after the return to glacial conditions appears to be a good candidate for numerical simulation. Additionally, a climate state during the transition from full glacial to interglacial may be investigated.

c. Full Glacial: Full glacial conditions will be studied in considerable detail using the selected GCM(s) as part of the model validation effort and PMIP/PCMDI. It is included in this list for completeness.

d. Super-Glacial: A super-glacial simulation is planned to account for glaciation more severe than the last glacial maximum at 18,000 BP to 21,000 BP. The most likely model for a super-glacial is 150,000 BP. Subtropical SSTs were colder at that time than during the last glacial maximum (Luz, 1973; Thompson and Shackleton, 1980; Crowley, 1981), terrestrial carbon changes were probably larger than during the last glacial maximum (Curry and Lohmann, 1982; Boyle and Keigwin, 1985/1986), and southern hemisphere winds may have been stronger than during the last glacial maximum (Thiede, 1979). As most of these changes represent extensions of the patterns inferred for the last glacial maximum (CLIMAP, 1981), the latter period can be used as an approximation to conditions upon which 150,000 BP changes will be superimposed. Existing simulations suggest that a larger North American ice sheet causes a more meridional flow pattern in North America (Shinn and Barron, 1989).

e. Super-Interglacial: Although this scenario also falls outside the subset of probable global states over the next 100,000 yr, a simulation is planned for inclusion in sensitivity studies. Likely candidates are simulations involving 4x and 8x present CO_2 concentrations, levels that might be approached as a result of complete exhaustion of fossil fuel resources (Keeling and Bacastow, 1977) and reduced absorption of emitted gases by the oceans and biosphere. Corresponding atmospheric temperatures could approach those for an ice-free earth (Thompson and Barron, 1981), although the ice sheets would probably still be present because of their inertial properties (Crowley, 1989).

f. Reduced North Atlantic Deep Water: Geologic data (e.g., Boyle and Keigwin, 1987) together with conjectures and model results for future transient climate change (Broecker, 1986; Washington and Meehl, 1989; Mikolajewicz et al., 1990), suggest that deep water production in the North Atlantic may be reduced for some global warming scenarios. Such a response would result in lower SSTs in the subpolar North Atlantic, a pattern that could affect the circulation pattern at Yucca Mountain through upstream adjustment of the planetary waves. To accommodate this effect, one sensitivity experiment with cold SSTs in the North Atlantic and warmer SSTs elsewhere (due to a CO_2 warming) is planned.

g. Extreme Greenhouse/Constrained Storm Track: Transient circulation changes could result in patterns other than a cold North Atlantic. On the basis of historical climate fluctuations, it may be possible to develop a set of global boundary conditions that might represent the greatest threat to the integrity of the Yucca Mountain site. To test this idea, one simulation is planned which will be made with very high SSTs (up to 8 times present CO_2) and the atmospheric circulation constrained to respond in a manner that delivers frequent low-pressure storm systems to the southwestern United States. Such a pattern may be unrealizable in the actual climate system. However, by taking advantage of our understanding of the behavior of circulation patterns, artificial boundary conditions that produce this result may be able to be developed, however unlikely they may be.

As already noted, the simulation of a climate state with candidate GCMs is dependent upon the specification of initial and boundary conditions for the selected state. Four key datasets must be specified to provide global climate boundary conditions for simulating past, present, and potential future climates corresponding to the selected global climate states. They are: (1) seasonal insolation at the top of the atmosphere; (2) atmospheric greenhouse gas composition and concentration; (3) ice volume and placement; and (4) SST distribution.

The latitudinal and seasonal distribution of energy from the sun over the surface of the earth drives atmospheric circulation. Past changes in the insolation field due to gravitational perturbation of the earth's orbital parameters by the other planets has significantly modulated climates during the last 2 million yr (Hays et al., 1976). The past and future insolation regimes can be calculated with a high degree of confidence for the next 200,000 yr. The insolation model is available as an acquired code (Berger, 1978).

The burning of fossil fuels and the release of radiatively important trace species are expected to result in a significant increase in the greenhouse effect by the middle of the next century (National Research Council, 1982; Dickinson and Cicerone, 1986; IPCC, 1990 and 1992). The resulting temperature and regional climate changes are anticipated to be significant (e.g., Manabe and Wetherald, 1986; Schlesinger and Mitchell, 1987; Ramanathan 1988; Crowley, 1989 and

1990) and may result in a climate realization unique in the earth's history. Because the half-life for removal of the CO_2 from the atmosphere is a few thousand years (Sundquist, 1985), an enhanced greenhouse effect will likely influence future climate at least over the next few thousand years. However, because of other human global impacts, eventual removal of the CO_2 from fossil fuel combustion may not return the climate system to its condition before the age of fossil energy.

There have been continuous variations in the CO_2 content of the atmosphere throughout the history of the earth, but the present and anticipated levels of CO_2 for the near future have not been equalled in tens of millions of years--certainly, never during the Pleistocene (Crowley and North, 1991). Although the mechanisms responsible for such fluctuations are not well understood, the record of atmospheric CO_2 fluctuations is available from ice cores (Barnola et al., 1987; Neftel et al., 1988) and can be explicitly specified for simulations of climate at least since the last interglacial. For simulations of climates of the more distant past for which direct CO_2 measurements do not exist, reasonable estimates can be made based on the similarity of CO_2 and ice volume fluctuations over the last 130,000 yr (Crowley and North, 1991).

The amount and spatial distribution of ice strongly affects the atmospheric circulation and is a necessary boundary condition for past and potential future climate simulations. These distributions are reasonably well known for the last 18,000 yr and are available as an acquired dataset from the NOAA National Geophysical Data Center (CLIMAP, 1981; Kutzbach and Guetter, 1986; Peltier, 1993). For simulations of global climate states prior to the last glacial maximum, the global ice volume is reasonably well known (Imbrie et al., 1984), but the spatial distribution of the ice less so. Nevertheless, reasonable estimates for ice volume and the area covered can be developed, as they can for potential future climate state simulations. Because of uncertainties, however, more than one set of boundary conditions may have to be stipulated for ice volume and area for each global state simulated in order to ascertain sensitivity to these conditions.

SSTs play a key role in forcing the atmospheric circulation and in determining total global precipitation. Reasonable estimates of SST distribution are available for the period since the last glacial maximum (CLIMAP, 1981; COHMAP, 1988). A more limited set of SST distribution estimates is available for more distant times (Imbrie et al., 1989). Conjectures supported by some modeling results suggest that substantial oceanic circulation changes may accompany global climate changes. In principle, one could use fully interactive coupled ocean-atmosphere GCMs (in which the ocean is represented in as much detail as the atmosphere and in which coupling is bidirectional) to ascertain these circulation changes and their effect on SSTs, but, in practice, these coupled models are in such an early stage of development that the results cannot presently be accepted with confidence. Fortunately, it is possible to include the effects of plausible ocean circulation changes in the numerical models by altering the SST distributions used as boundary conditions for each selected global state. Consequently, more than one set of boundary conditions for SST distribution may need to be run for each global climate state to be simulated.

It should be noted that justification for the selection of each specified global climate state and the reasoning behind the development of each set of boundary (and initial) conditions needs to be documented as part of this task. Confidence in the process will be enhanced by making use of a range of expert opinion early in task execution.

2.4 Nested Global-Regional Climate Modeling, Activity 8.3.1.5.1.6.2.

After evaluating, selecting, and validating the GCM to be used and developing GCM initial and boundary conditions for the selected global climate states, regional conditions will be inferred from the results of the nested GCM-RegCM approach described here.

2.4.1 Regional Climate Model Selection

As with GCMs, there are a fair number of RegCMs available in principle, but not in practice. In particular, only a few have been modified to accommodate nesting with GCMs and to treat surface processes in detail. For the last several years, a group at the NCAR has been working with RegCMs based upon the NCAR-Pennsylvania State University limited area model MM4 (Anthes et al., 1987). There is considerable positive experience with this model in a nested environment. For that reason, the current version of that model, RegCM2 (Giorgi et al., 1993a and 1993b), has been tentatively selected for use for the nested GCM-RegCM activity. A detailed description of RegCM2 is given in the references cited, along with commentary on how it differs from its predecessors. Documentation of the justification for the final RegCM selection is an integral part of this task.

2.4.2 Regional Climate Model Validation

In a nested GCM/RegCM environment, climate simulation errors can originate either from the large-scale fields provided by the driving GCM (e.g., location and intensity of the jet stream and storm tracks) or from the internal physics of the RegCM. The former source of error is handled by the element of GCM model validation that focuses on present climate reproduction of the RegCM boundary conditions (Section 2.3.1). The main goal of the RegCM validation in the present task is to identify, quantify, and, if possible, correct model biases and uncertainties due to RegCM physics formulations and model configuration (e.g., domain size and model resolution). This RegCM validation is carried out primarily by performing sets of long-term simulations with the RegCM driven by present-day observed meteorology (wind components, temperature, and water vapor as a function of altitude and surface pressure) processed into the necessary initial and boundary conditions interpolated from the European Centre for Medium-Range Weather Forecasting gridded weather analyses (Trenberth and Olson, 1988). The basic assumption is that, because the driving meteorological fields are taken from observed datasets and are thus realistic, model errors are mainly due to deficiencies in the internal model physics. The quality of the validation, conducted in much the same manner as that described for the GCM validation, is evaluated using standard statistical techniques and other more objective techniques developed for this purpose.

2.4.3 Nested Global-Regional Climate Model Validation

After RegCM biases are defined, quantified, and to the extent practical, corrected, validation of the combined GCM/RegCM system is to be initiated by analyzing its ability to reproduce present-day climate conditions over the region of interest. For validation, a GCM present-day climate simulation is first performed and evaluated against available observations (as described in Section 2.3.1). The

GCM model output then is used to drive the nested RegCM and the RegCM-produced high-resolution climatology compared with available high resolution regional observational datasets, e.g., the European Centre for Medium Range Weather Forecasting datasets (Trenberth and Olson, 1988) mentioned above. This comparison, along with the previous separate RegCM and GCM validation tests, gives quantitative information both on the ability of the coupled model system to simulate the climate of the region and on the relative contribution of the driving GCM and the nested RegCM model components to total model system biases.

After model performance in reproducing present-day climate conditions over the region of interest has been evaluated, further experiments will be done to test the coupled model system's ability to reproduce climate conditions different from the present. This validation experiment will be done by comparing modeled paleoclimate conditions with periods for which high quality data are available on both model boundary conditions (SSTs, ice sheet, sea ice, and vegetation cover) and the southwestern regional climate. The principal candidate for such a paleoclimate period is the last glacial maximum 18,000 BP to 21,000 BP (Benson et al., 1990; CLIMAP, 1981). The procedure for the paleoclimate validation analysis is similar to that described for the present climate. A GCM paleoclimate simulation is first performed. The meteorological output from this simulation then is used to drive the nested RegCM over the region of interest and the model climatology compared with available paleoclimate evidence. The principal difference is that the uncertainties are much larger for the paleoclimate validation than for the present climate validation.

2.4.4 Potential Future Climate Simulations

The present climate and full glacial validation runs (Sections 2.3.2a and c, respectively) are useful not only for validation, but also as potential future climate simulations. Several other future climate runs, however, have also been selected (Sections 2.3.2b, d, e, f, and g). These future climate simulations proceed in a similar manner. The GCM climate simulations for the identified potential future global climate states are performed first, using the global initial and boundary conditions (developed in Section 2.3.2). The meteorological outputs from these simulations then are used to drive the nested RegCM for each case over the region of interest. The difference is that, for potential future climates, there are no available climatological data against which to compare the results. However, one can compare the results against paleoclimate data for roughly similar global climate states to ascertain whether the results are reasonable. This comparison will be done to the extent possible.

2.5 Site-Specific Model Output Adjustment, Activity 8.3.1.5.1.6.3

2.5.1 Spatial Interpretation

The results from the nested GCM/RegCM model system require further processing both for comparison with available data acquired at specific locations within the region (in the case of the model validation runs) and for use in development of RLCSs for the potential repository site (Section 2.6).

If greater spatial detail regarding the distribution of climatological parameters is required for hydrologic or performance modeling, development of a representation of regional climate model results on a more localized scale will be pursued. At best, the regional climate models provide average values of climatic parameters for a grid size of roughly 100 square kilometers in area; if variations in these parameters on the scale of more localized topographic features, such as ravines, washes, and hillsides, are desired, a means of accounting for these finer scale variations must be developed. As mentioned in Section 2.2 above, in principle, all of these effects could be taken into account by yet another level of model nesting. However, fine-grained models suitable for such double nesting do not yet exist. Hence, the most attractive presently available option is to use empirically derived adjustments for this effort.

While these various corrections could be formulated without recourse to empirical data, more realistic results are likely using empirical data. For instance, it can be empirically determined how precipitation (as well as temperature, winds, etc.) varies with elevation in the region of interest (Wigley et al., 1990; Karl et al., 1990). The empirical relationships then can be used to adjust the output of the nested modeling system for the elevation of interest. It can also be empirically determined how the meteorological parameters of interest vary at the same elevation from the windward to the leeward sides of slopes. Adjustments to the regional predictions based on those empirical relationships can also be applied.

Other alternatives may be evaluated for addressing the adjustment of regional scale results to a more site-specific scale, including for example, developing or applying existing models that relate precipitation and temperature distributions to topography.

2.5.2 Temporal Interpretation

The nested GCM/RegCM model results, corrected for local effects as indicated in Section 2.5.1, provide predictions of the relevant climatic conditions at the site of interest for the selected potential future global climate states (discussed in Section 2.3.2). However, it is still necessary to take into account the time dependence of meteorological conditions (on time scales from fractions of an hour to tens of thousands of years) to adequately treat the hydrology of any given area of interest. The climate models simulate representative conditions of a selected climate state over relatively short time periods (several years) with respect to the millenia over which waste isolation must be maintained. For processes operating on time scales less than the simulation period, standard statistical methods can be used. The longer time scales (centuries to tens of millennia) involved in using these simulation results in the synthesis of RLCSs (Section 2.6) require a different approach. The slow temporal dependence of the parameters of interest can be empirically modeled using the information provided by the integrated chronology and paleoclimate description that is the product of SCP Study 8.3.1.5.1.5: Paleoclimate/Paleoenvironment Synthesis. This chronology provides an example of how the parameters of interest have varied in the past between the climate states of interest (those which have occurred). It is assumed that the paleoclimate chronology provides a basis for describing the longer-term climatic behavior, including the sequential development and establishment of different climate states over long time periods. On the basis of this first approximation, reasonable temporal scenarios connecting the present climate with the selected future climate states can be developed for use in the RLCSs for the Yucca Mountain site (Section 2.6). Some adaptation to account for uncertainties inherent in this assumption, such as human-induced effects not present in the past record, may also be incorporated in the treatment of some of the scenarios developed in the RLCS synthesis activity.

2.6 Future Climate Synthesis, Activity 8.3.1.5.1.6.4

The final activity in this study, Future Climate Synthesis, draws on all available information relevant to future climate at the Yucca Mountain site through the mechanism of RLCSs. By definition, the RLCSs specify the time dependence over the next 100,000 yr of all the meteorological parameters necessary to model hydrology for each scenario. The RLCSs are not predictions of how the relevant meteorological parameters will vary at the candidate Yucca Mountain repository site over the next 100,000 yr, but rather, constructs of how those parameters could credibly vary. A likely specification for one RLCS is the general glacial state producing the most serious credible threat to repository integrity. A specification for another RLCS is the scenario connecting the present climate to the most serious credible interglacial threat to repository integrity. A third is the expected scenario--the best current estimate of what is most likely to happen. The foregoing possibilities may be further refined and yet others added. The objective is to construct RLCSs that span the range of credible (reasonably likely) future local climate scenarios in such a way that, if it can be shown that the repository performance would be acceptable for this set of RLCSs, it is highly probable that it would also be acceptable for any other credible scenario.

The approach put forward has much in common with the design basis accident approach used in nuclear facility design. Like the range of possible climates, the range of possible accidents is so large that it would be impossible to investigate in detail the probable consequences of each possibility. All one can do is to identify classes of possible accidents (or climates) which may pose significant threats, and assure that the design is sufficiently robust such that the results would be acceptable even if the most severe credible accident (most challenging RLCS) in each category occurred.

Clearly, development of RLCSs will require considerable interaction with anticipated users of the information to be produced. These potential users include those involved directly in assessing the long-term waste isolation performance of the potential repository system and those responsible for modeling the future hydrology of the Yucca Mountain site. Their input will be useful in helping to guide the specification of RLCSs and the definition of the interface between the future climate modeling effort and the subsurface hydrologic modeling effort.

In supporting these users, other RLCSs may be developed for use in evaluating additional hypotheses or specific conditions affecting hydrology or performance. Although this study is biased toward the evaluation of possible climate states that challenge repository integrity, scientific confidence in the waste isolation performance may be enhanced by including more reasonable variations in future climate in the set of RLCSs. For example, these alternative scenarios could include the development of climate changes similar to those that occurred in the recent past or of future climate evolving as a small perturbation on present climate conditions. Another perspective, provided by users of the results of this work, may also influence the direction of this synthesis activity. If subsurface hydrological processes or conditions are hypothesized that could adversely affect performance, for example, this study may provide some insight on the circumstances under which those conditions might develop as a result of climatic processes.

Like the design basis accident approach, the RLCS approach offers a process for evaluating additional suggested generic scenarios. Here, two questions are relevant:

- Is the proposed additional generic scenario credible (reasonably probable)?
- Is the proposed generic scenario likely to stress repository integrity more severely, or in a significantly different way, than the set of already-analyzed RLCSs?

If, in light of all available information, the answer to either or both is "no," there is no need to go any further. If the answer to both is "yes," one needs to develop the proposed generic scenario into another RLCS and to analyze the resulting hydrology.

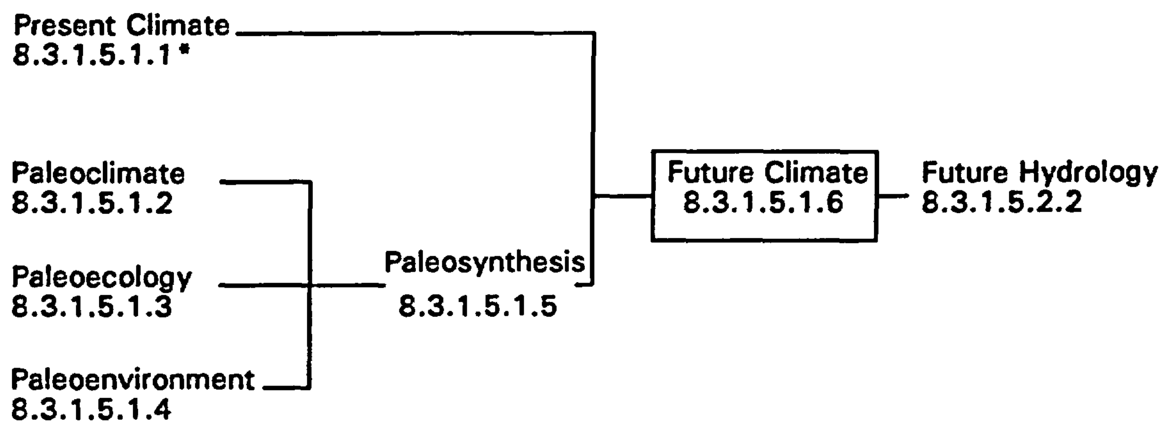
3.0 APPLICATION OF RESULTS

The climate program described in the SCP consists of Investigation 8.3.1.5.1, which investigates past, present, and future climate conditions, and Investigation 8.3.1.5.2, which examines the effects of future climate change on the hydrology of the Yucca Mountain site. The future climate modeling activity described in this study plan for SCP Study 8.3.1.5.1.6 builds upon the information developed regarding past and present climates by other studies within Investigation 8.3.1.5.1 (and the meteorology program, 8.3.1.12, which may assume much of the original scope of 8.3.1.5.1.1 regarding the present climate) and provides input information primarily to Investigation 8.3.1.5.2 for use in modeling future hydrology (see Figure 4).

Resolution of several of the issues in the issues heirarchy defined in the SCP as an approach to organizing and addressing site characterization concerns depend upon the information generated by this study. Issues identified in the SCP whose resolution will utilize the results of this study are listed in the following table.

Table 1. Site Characterization Issues Associated with SCP Study 8.3.1.5.1.6

SCP Issue	Short Title	SCP Section
1.1	Total system performance (the system performance objective for limiting radionuclide releases to the accessible environment as required by 10 CFR Part 60 and 40 CFR 191.13)	8.3.5.13
1.8	NRC siting criteria (the favorable and potentially adverse conditions of 10 CFR 60	8.3.5.17
1.9a	Higher level findings (postclosure) of 10 CFR 960: (1) 960.4-2-1, qualifying condition for geohydrology, (2) 960.4-2-4, qualifying condition for climate.	8.3.5.18
1.9b	Comparative evaluation over next 100,000 yr.	8.3.5.18



(* This interface may be replaced by 8.3.1.12.1.1, Current Regional Meteorology.)

Figure 4. Investigation 8.3.1.5.1 Interfaces

Hydrologic modeling is essential to the assessment of repository performance, particularly with respect to waste isolation and the demonstration of regulatory compliance. A surface hydrology model must bridge the interface between the atmosphere and subsurface and therefore requires development of an understanding of the coupling between atmospheric climate processes and subsurface hydrologic processes. SCP Study 8.3.1.5.2.2, "Characterization of Future Regional Hydrology Due to Climate Changes" is limited to surface and saturated zone hydrologic analysis; SCP Study 8.3.1.2.2.9, "Site Unsaturated-Zone Modeling and Synthesis," addresses the impacts of climate change on the unsaturated zone hydrology. However, specific interfaces and information transfers between these two studies and the future climate modeling study are not yet well-defined. More specific interfaces will be defined as the approach to these related studies matures.

Bounding values for the dependent variables of interest to the hydrologic modeling provided by this future climate modeling study can also be used to support the identification and selection of analog study locations, locations that behave in a manner analogous to the anticipated future hydrologic behavior of the Yucca Mountain site.

Although the primary use of the results of this study is to generate the source term for the purpose of modeling hydrology, indirect interfaces also exist with several other issues. A knowledge of expected changes in site characteristics will be useful in designing system elements, including the waste package, underground facility, and sealing of underground openings, which are the subject of Issues 1.10, Postclosure Waste Package Characteristics; 1.11, Postclosure Underground Facility Configuration; and 1.12, Seal Characteristics, respectively. Information from this study, as well as from other elements of the climate program, may also be useful to other program elements, including the geohydrology program, SCP Section 8.3.1.2; the geochemistry program, SCP Section 8.3.1.3; and the erosion program, SCP Section 8.3.1.6.

SCP Table 8.3.1.5-2 identifies a number of future climate parameters, which are to be supplied by this study as input to the resolution of the design and performance issues, including seasonal distribution and average annual rainfall, storm types and intensities, distribution and annual average snowfall and rapidity of snowmelt, evapotranspiration, cloud cover, temperature, and wind speed and direction. The associated hydrologic parameters of interest include precipitation-runoff conditions, infiltration, percolation, the degree of saturation, the thickness of the unsaturated zone, and the altitude and gradient of the water table.

4.0 SCHEDULE

Conceptually, the approach to this study involves the four inter-related activities described in Section 2, the performance of which is dependent on resource availability, schedule constraints, and changes in program strategy. The selection and validation of the computer software used for climate modeling is the first task, and is expected to require approximately one year. This will be followed by approximately a one-year effort to validate the model processes encoded in the software through comparison with available information on current climate and well-established paleoclimate states. At least one, but probably less than three, years of effort are anticipated for the numerical simulation of selected potential future climate states. In parallel with these efforts will be the effort to develop and apply site-specific model adjustments. The synthesis of the modeling results to support of hydrologic and performance modeling needs and develop a defensible representation of the future regional climate and environment for the Yucca Mountain area will be initiated as simulation results become available, and will likely extend an additional year beyond completion of the planned simulation runs. More detailed and current cost, schedule, and performance information for this study is maintained in the YMP Planning and Control System under Work Breakdown Structure Element 1.2.3.6.2.1.6.

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