DEVELOPING AN APPROACH FOR DETERMINING LONG-TERM ECOLOGICAL POTENTIAL AT YUCCA MOUNTAIN

Presentation to:

NWTRB PANEL ON ENVIRONMENT
AND PUBLIC HEALTH

Presented by:

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March 22, 1994
Las Vegas, Nevada

ECOLOGICAL POTENTIAL

- The capability of an area to sustain a functional ecosystem and maintain its integrity, regardless of the species involved.

THE QUESTION FOR ENVIRONMENTAL PERFORMANCE ASSESSMENT

- Can thermally-induced impacts from a hot repository alter the surface environment to the extent that repository performance might be affected?

APPROACHES AND CONCEPTS ADOPTED

— The unified ecosystem approach

— Ecosystems as interactive networks

— The process-functional approach

— The expert advisory panel approach

— Environmental forcing factors and the resource-based approach

ENVIRONMENTAL VARIABLES

— Environmental forcing factors are external variables that drive an ecosystem, such as atmospheric CO_2, temperature, and moisture.

— State variables are internal variables that define ecosystem potential. Examples include the concentrations of nutrients, the abundance of a particular component of a trophic level, and the microbiota that contribute to the rhizosphere.

ENVIRONMENTAL FORCING FACTORS FOR THE YUCCA MOUNTAIN CASE

— Atmospheric CO_2

— Atmospheric temperature

— Subsurface temperature

— Precipitation and soil moisture

INFORMATION NEEDED ABOUT SUBSURFACE TEMPERATURE

— Temperature increase, peak, and time period.

— Temperature profile in the root zone.

— Area affected and pattern of change.

— Changes in soil moisture.

— Changes in local climate.

ASSUMPTIONS ABOUT THE AFFECTED AREA

— The affected area will cover about $7km^2$.

— Temperature increases begin after 200-300 years.

— Peak temperatures reached after 600-800 years.

— Above-normal soil temperatures for a few thousand years.

— Temperatures to 6-7m below the surface from 2^o-13^oC.

— Increases will not be uniform by depth or at the surface.

— Information is lacking on local climate and soil moisture.

POSTULATED TIME LINE FOR CLIMATE CHANGE WITH HOT REPOSITORY SCENARIO INCLUDED

8000 yrs.	global warming abates
3000 yrs.	peak subsurface temperature maintained
700 yrs.	peak subsurface temperature
300 yrs.	subsurface (6-7m) temperature increases
....	....
150 yrs.	air temperature increases $2^{o}C$; additional ecosystem stress occurs
70 yrs.	ecosystem stress occurs
50 yrs.	air temperature increases another $1^{o}C$
0 yrs.	air temperature has increased $1^{o}C$

THE CHALLENGE TO DETERMINING LONG-TERM ECOSYSTEM POTENTIAL

Identify the minimum number of components and connections within the ecosystem network needed to understand how an ecosystem operates and how it will respond to environmental forcing factors.

Use this information along with associated quantitative models to predict long-term ecological potential.

SOME ISSUES IMPORTANT TO ECOSYSTEM POTENTIAL

— Primary production and rates of resource capture.

— Interactions between vegetation and soil.

— Effects of water and nitrogen on plant growth.

— Interactions between the effects of temperature and CO_2.

— Water budget, roots, the rhizosphere, and nutrients.

SUMMARY AND CONCLUSIONS

— Use a resource-based approach and predictive models.

— Ecosystem integrity is the end point for ecological potential.

— Global warming impacts will precede repository impacts.

— There are no predictive models of natural ecosystem networks.

— Soil-water-plant-atmosphere interactions are critical.

— Use worse-case scenarios until empirical data are available.

POSTULATED EXTREME SCENARIO FOR ENVIRONMENTAL RESPONSES TO A HOT REPOSITORY AT YUCCA MOUNTAIN

1. Subsurface temperature and local climate are altered.

2. Vegetation is reduced and precipitation is increased.

3. Runoff and infiltration increase.

4. Erosion and bedrock exposure increase.

5. Vegetation is eliminated.

6. Erosion and infiltration are maximized.

7. **Would the performance of a repository be influenced?**

RECOMMENDATIONS

— THE DOE SHOULD INTEGRATE ENVIROMETAL ASSESSMENT WITH PERFORMANCE ASSESSMENT TO ADDRESS THE ISSUE OF LONG-TERM REPOSITORY PERFORMANCE. PROCESS-BASED ECOSYSTEM ECOLOGY IS ESSENTIAL TO SUCH AN EFFORT AND SHOULD BE INITIATED SOON WITHIN THE YUCCA MOUNTAIN PROJECT.

— THE STATE ENCOURAGES THE DOE TO CONVENE AN EXPERT ADVISORY GROUP TO GUIDE THE YUCCA MOUNTAIN PROJECT WITH RESPECT TO THE LONG-TERM ECOLOGICAL POTENTIAL OF THE SITE AND ITS CONSEQUENCES TO REPOSITORY PERFORMANCE.

— THE STANDARD ADOPTED FOR STUDYING THE LONG-TERM ECOSYSTEM AT YUCCA MOUNTAIN SHOULD REFLECT THE BEST THAT ECOSYSTEM SCIENCE CAN OFFER INSTEAD OF REFLECTING THE MINIMUM EFFORT FOR ACHIEVING LEGAL SUFFICIENCY.

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Following the November meeting of this group the State of Nevada has focused its environmental activities on the long-term ecological potential of the Yucca Mountain site. By "ecological potential" we mean the capability of a spatial area within a time scale to sustain a functional ecosystem and maintain its integrity, regardless of the species involved.

Our goal has been to develop a basis from which we can conduct oversight and review of the issue of ecosystem responses that might result from a repository where induced thermal effects result in elevated near-surface temperatures. The concept of ecological potential is a practical means of trying to examine the potential ecological effects of a "hot" repository. Looking at long term ecosystem potential at Yucca Mountain also provides a means for addressing the question of whether near-surface thermal impacts to the environment could have a feedback effect on repository performance through increased erosion and infiltration.

In pursuing these issues we have followed a unified ecosystem approach based in part on the 1992 book by Allen and Hoekstra and the concept of ecological heirarchy which the book itself reflects.

Integrated into this context is the interactive network concept of ecosystems championed by Higashi and Burns in a paper in their 1991 book on theoretical ecology.

We also have chosen to adopt the process-functional approach to studying ecosystems as opposed to the population-community approach currently being pursued by DOE at Yucca Mountain. Population-community ecologist view ecosystems as groups of interacting populations where the biota are the ecosystem and the abiotic environment is the backdrop for biotic interactions. The process-functional approach, as discussed by O'Neill and others in 1986, considers organisms and their physical environment as a single integrated system or interactive network where the focus is on physical-chemical-biological processes that permit an ecosystem to function.

In attempting to conceptualize an ecosystem approach one is faced with the overwhelming complexity of the system. John Wiens and his colleagues, in a 1992 publication, applied an ecosystem approach to Mono Lake in assessing alternative management strategies for the ecosystem. The investigators had access to an interdisciplinary advisory panel that helped guide the assessment by identifying, evaluating, and integrating critical ecosystem processes and interactions that had to be addressed. The expert panel's guidance led to a synthesis that would not be likely to result from the efforts of one or a few individuals. The use of such a panel seems essential to an effort like that discussed here, although our work has not proceeded to that stage.

Another notable piece of work that contributed significantly to our efforts toward developing a framework for addressing future ecological potential at Yucca Mountain was that of Christopher Field and his colleagues, published in 1992. These researchers used the concept of "environmental forcing factors" (EFFs) to gain insight into the effects of increasing atmospheric concentrations of CO_2 and enhanced atmospheric temperatures on terrestrial ecosystems. EFFs are external variables that drive an ecosystem, such as atmospheric CO_2, temperature, and moisture. "State variables", on the other hand, are internal variables that facilitate an ecosystem's realizing its potential. Examples of state variables are the concentrations of nutrients, the abundance of a particular component of a trophic level, and the microbiota that contribute to the rhyzosphere. Field and his three coauthors used an informal group of distinguished experts to review and guide their work in a manner comparable to the formal asvisory panel used by Wiens and others.

Involved with the immense complexity of an ecosystem are the myriad interactions between EFFs and state variables. The relationships between these two types of factors are seldom linear due to the buffering effects of state variables on EFFs. This leads to questions about the magnitude of changes in an ecosystem that will be caused by EFFs. In an effort to predict the potential condition of an ecosystem one must understand the relationship between EFFs like soil temperature and moisture and the state variables like mycorrhizae and nitrogen. Field and others showed that the effects of EFFs like atmospheric temperature on terrestrial ecosystems can be assessed in terms of the resources needed by the biota for growth. These resources include, among other things, light, oxygen, CO_2 and other carbon compounds, water, and nutrients. Note that CO_2 and water can be EFFs as well as required resource while temperature can be an EFF and a resource modulator, i.e., temperature is not consumed but it acts on productivity and other process rates. This is the approach we adopted for developing a preliminary conceptual framework for addressing ecological potential at Yucca Mountain in response to the EFFs associated with global warming and a hot repository.

To apply the resource-based approach for analyzing the consequences of EFFs to ecosystem potential requires identifying the critical ecosystem and resource compartments that will be influenced by the EFFs. In the case of the Yucca Mountain site there appears at this stage to be perhaps four EFFs involved including atmospheric CO_2, atmospheric temperature, subsurface temperature, and probably water. Data from past studies of the responses of biota and ecosystem processes to soil fertility, carbon compounds, water availability, and temperature provide a starting point for assessing ecosystem responses to EFFs and for planning research on the long-term potential of an ecosystem like Yucca Mountain. Identifying these functional compartments is where an expert advisory panel is needed.

What information would a panel need in order to meld an ecosystem approach with the resource-based concept? With respect to a hot respository, the first thing a panel might wish to know would be the characteristics of the EFFs involved, i.e., increased subsurface temperature and changes in moisture availability. For example: When will a temperature increase first reach the root zone, when will it peak, and how long will the increase persist? What will the subsurface temperature profiles at these times be? How large an area will be affected and what will be the distributional pattern of increased temperature? What changes in soil moisture will accompany the temperature changes, and will the two influence local climate conditions, e.g., via wintertime fog?

For the State's purpose we have used information mostly available in the literature on the Yucca Mountain Project. For example, the shape and size of a thermally affected area above a repository is assumed to be roughly circular and 7-8km^2 in area. One scenario predicts that the subsurface zone of interest, to a depth of 6-7m, would begin experiencing increased temperature about 200 years after a repository is filled, and a peak temperature in the subsurface zone of interest would be reached after 600-800 years. How long the peak would hold is uncertain but above-normal soil temperature at Yucca Mountain probably could be expected for a few thousand years, depending on the characteristics of the waste. As for the anticipated temperature profile and distributional pattern, we have assumed a profile in the uppermost 6-7m below the surface from about a 2°C temperature increase at the surface to about a 13°C increase at depth. Because of the fractured nature of the rock at Yucca Mountain, the temperature will not be uniform at various depths or across the surface. Complications at the surface also will result from the complex ecotopographic diversity at the site. For these reasons we are assuming a pronounced mosaic of temperatures within the top 1-3m of the surface, where most roots occur, ranging from a 2°C to 6°C temperature increase with extreme increases of from 20°C to 40°C where fractures extending from the repository vent at the surface. Of course there is a high degree of uncertainty in these assumptions that remains to be resolved. Until then it seems wise to work with scenarios that approximate the extremes.

Questions about the nature of the ecosystem at Yucca Mountain when the subsurface temperature begins to increase due to a hot repository need to be explored. This would probably occur in about 250 years from now. Because of the anticipated effects of global warming, which could be in full swing by that time, it cannot be assumed that the ecosystem around the year 2250 will resemble its present condition. The question then becomes how to determine the potential of the ecosystem after another 250 years. This is where the resource-based approach and the appropriate EFFs would first be applied.

Climatologists believe that a doubling of preindustrial CO_2 levels in the atmosphere ultimately will lead to an increase in global mean temperature of about 3°C. Present temperatures already are 1°C above preindustrial levels and substantial stress to ecosystems is likely within the next 50 years. The ultimate rise to 3°C or greater will occur at a rate 10-100 times faster than has occurred previously. Of course there is considerable uncertainty about the rate of global warming, but for our purpose we are assuming that the peak increase will occur in another 200 years. This is reflected in Figure 1 at the back of this paper.

Global warming is likely to dominate the earth's climate for several thousand years, and after 5,000 to 10,000 years it is assumed that atmospheric and climatic conditions will return to normal. The response of vegetation to changing climatic conditions is known to lag behind climate changes by decades or even centuaries. Thus, it must be assumed that during the period that thermal impacts from a repository are reaching the root zone at Yucca Mountain and building to a peak, the vegetation and indeed the ecosystem will already be in a transitional stage that is difficult to understand and predict in terms of ecological potential. In the longer term, during the 10,000 year-lifetime of a respository, it may be necessary to address the issue of a return to full glacial conditions that some expect could begin to occur in as early as another 9,000 years.

Insight can be gained into this from the resource-based approach using atmospheric CO_2 and temperature in concert with subsurface temperature increases and changes in soil moisture as EFFs. How far into the future and with what degree of certainty predictions can be made remains to be determined. On thing seems clear: The resource based approach will not provide predictions of the species and communities that will exist at a site but will help define the potential conditions of the ecosystem and whether the conditions would be favorable or adverse.

Knowing the parameters and characteristics of the EFFs, an expert advisory panel would face questions about the functional processes of the ecosystem that must be considered in predicting ecosystem potential. The processes, interactions among them, and the feedback mechanisms involved are so numerous and complex that ecosystem ecologists and modelers are not able to successfully model them and predict the nature and composition of future ecosystems. The challenge then is to identify the minimal number of components and connections within the ecosystem network that are needed to understand how an ecosystem operates and how it will respond to the EFFs at issue. This is one of the major challenges in attempting to determine long-term ecosystem potential and it is here an interdisciplinary group is needed.

Plants apparently are the dominant factor that determines an ecosystem's potential condition. The plants are dependent on adequate moisture, temperature, and nutrients within the soil. In turn, the plants interact with and influence the soil. Several important feedback mechanisms exist within the soil-water-plant functional system that involve, among other things, annual net primary production, organic content of the soil, decomposition and nutrient cycling rates, and plant symbionts like mycorrhizae and nitrogen fixing bacteria. These interactions are strongly influenced by the amount of CO_2 in the atmosphere, atmospheric and subsurface temperature, and soil moisture, the EFFs of interest to the Yucca Mountain site.

Thus, plant production is a principal factor regarding ecosystem responses to EFFs because production determines rates of resource capture and availability to consumers and decomposers. The low growth rates of desert plants like those at Yucca Mountain often is associated with a high root:shoot ratio. If increased atmospheric temperature from global warming lead to increased respiration and reduced carbohydrate status, plants will allocate more biomass to shoots and less to roots. This type of effect from an EFF would affect the status of all other aspects of the ecosystem. Complications also would exist from increases in transpiration due to elevated ambient temperature.

Water and nitrogen have the greatest effect on plant growth when these resources are limited as in the case of Yucca Mountain. If global warming were to increase drought conditions, reduced availability of nitrogen also would occur. Low nitrogen availability in turn alters water use efficiency. Further complications to these interacting functional processes will result from an increase in ambient CO_2 concentrations. These are the kinds of complications in functional processes likely to result from global warming. What will happen when increases in subsurface temperature from a hot repository are imposed on the ecosystem? The contrasts between the effects of temperature and CO_2 blur attempts to predict future ecosystem potential at Yucca Mountain. Keep in mind that it is not the species that inhabit the thermally altered long-term ecosystem at Yucca Mountain that are important but whether or not the processes on which ecosystem integrity depends will remain functional.

Another important factor regarding vegetation is its generic role in maintaining carbon balance in a ecosystem. Aboveground net primary production is the principal source of organic matter for soil. The flow of carbon from shoots through roots and into the soil is one of the key processes in terrestrial ecosystems. It is important to know how the EFFs involved with the Yucca Mountain ecosystem will influence net carbon flux and carbon allocation within the ecosystem because the potential of the ecosystem will depends in part depend on these processes.

Water balance is another factor that is sensitive to ecosystem processes, and vice versa. For example, ecosystem water balance is sensitive to root depth, and this is important at Yucca Mountain with respect to increasing subsurface temperature and the potential for root mortality and for effects on the rhizosphere. The anticipated changes in water balance due to thermal impacts will be important to determining ecosystem potential.

The length of the growing season at a thermally impacted site also is important. Subsurface heat at Yucca Mountain could limit the growing season to portions of the winter season. Such a radical alteration would doubtlessly have a profound influence on ecological potential at Yucca Mountain. This in turn would have a drastic impact on animals and on trophic dynamics. Little is known about these interactions and effects but it seems possible that studies could be carried out in microcosms once more is know about the nature and parameters of the EFFs that will be involved at Yucca Mountain. Indirect effects and ecosystem level feedbacks will be more difficult to understand because so little is known about how to address them with respect to the fauna and trophic dynamics.

Likewise, the effects of global warming and thermal impacts from a repository on soil processes will be difficult to resolve. Given the importance of vegetation in determining ecosystem conditions, predicting the responses of soil to EFFs will in large part depend on predicting changes in vegetation.

How can research help resolve the uncertainties concerning long-term ecological potential at Yucca Mountain? There is much to learn in this regard from some of the ongoing research approaches being taken toward global warming. For example, John Harte and his colleagues at the University of California, Berkley, have taken a novel approach by heating plots in an alpine meadow from overhead and studying various ecosystem processes, especially in the soil. Harte and others have one manuscript in press and five others in review. The paper currently in press addresses soil temperature and aspects of water balance. The heat lamps used raised summertime soil temperature by 3°C and reduced summertime soil moisture by as much as 25%. The results highlighted the role that vegetation plays in influencing soil responses and has implications for rates of nutrient cycling and primary production that are to be covered in some of the remaining manuscripts. Harte and others also noted that the study approach used for the work holds promise as a means for understanding the bi-directional linkages among climate, vegetation, and soil that lead to feedback mechanisms that alter ecosystems.

There have been a small number of studies where buried electic wires were used to heat the soil from beneath the surface. This approach resulted in sharp temperature gradients near the wires and requires disturbing the soil to install the wires. Thus, the usefulness of the approach for studying the Yucca Mountain case is questionable but deserves consideration.

Others have suggested gaining insight to the ecological potential at Yucca Mountain by studying both active and fossil geothermal sites in Nevada as well as looking into the possibility of conducting experimental field plot studies that would be heated via pipes from nearby geothermal sites. These and other avenues for obtaining empirical data on the consequences of subsurface heat to the ecosystem at Yucca Mountain should be considered.

There is another avenue of study that deserves to be mentioned. In the past there have been suggestions for using geologic conditions as analogs for future global warming. This paleoecological approach currently is seen differently than it once was. One reason is that greenhouse warming probably represents a unique climate condition in the earth's history and there is no warm period in the geologic past that is a satisfactory past analog to global warming. The same will of course hold for thermal effects of a hot repository. Multiple impacts at Yucca Mountain in the future will produce effect that are different from any that have ever occurred before. Ecosystem scientists have learned that functional processes, interactions, and feedback are too important and too complex for past ecosystem conditions to ever be repeated again at any particular site. It has also been learned that biotic communities do not migrate as units with changing environmental conditions. In other words, the responses of particular species to climatic changes in the past have been individualistic and will be so in the future. While climatology and paleoecology will have a role to play in determining ecological potential at Yucca Mountain, alone they cannot be used to predict future ecological conditions.

In closing, I will summarize the findings of our preliminary work on long-term ecological potential.

- Insight to the impacts of EFFs like CO_2, atmospheric temperature, and below ground temperature and moisture on terrestrial ecosystems can be gained from considering their effects on the resources needed for ecosystem function. The resource-based approach in the context of a unified approach to ecosystem science provides a framework for quantitative models of these interactions for addressing questions of long-term ecological potential.

- Most ecosystems are exposed to a combination of atmospheric EFFs but increased temperature arising from belowground poses an uncommon situation. Accurate predictions of ecosystem potential at Yucca Mountain will need to account for this factor and for attendant changes in environmental conditions like soil moisture, decomposition rates, carbon flux, and rates of nutrient cycling. Preceeding the effects of hot repository there will be near-term impacts on these factors as a result of global warming. Before the thermal effects of a repository have dissipated, ecological complications could occur from a return to glacial conditions.

- An ecosystem will always be changed when environmental conditions, like the EFFs discussed here, are altered. Models that predict the future by shifting existing communities around or that rely on paleoecological analogs commit mistakes in assuming that past ecosystem interactions will be repeated in the future. Future ecosystems will differ from those in the past and there are no analogs for them in the geologic time scale.

- The ecological potential of a site impacted by EFFs will depend on the capability of the site's altered environment to sustain an ecosystem and maintain ecosystem integrity. For example, the potential of an affected ecosystem will depend on the availability of species adapted to the EFFs and the resources available to migrate to the site. A variety of alternative species may be available that can fit the altered environmental condition of the site and contribute to ecosystem function. If not, the altered site will lose its ecosystem integrity, become disfunctional, and remain so until a match between compatible environmental conditions and biotic components is achieved.

- It is unlikely that ecosystem science will ever have sufficient information and insight to all functional processes that would be needed to describe an ecosystem in detail and to develop predictive models of the complete network. What is important is to identify and understand a managable number of processes that can be used as surrogates for modeling the whole system.

- Advances in biophysical ecosystem ecology have provided a sound basis for understanding the responses of some functional processes to physical factors of the environment. Models are available for coping with changes in some EFFs and the corresponding responses of some ecosystem functions. Thus, some effects of EFFs on ecosystem processes are sufficiently understood to address a case like Yucca Mountain while others are not.

- Soil-water-plant-atmosphere interactions and feedbacks seem to be of primary importance in determining future ecosystem potential, especially in deserts. Understanding these relationships, interactions, and feedback mechanisms is fundamental to predicting ecological responses to EFFs. Some of these relationships are reasonably well understood while others are not and require further research.

- The ecosystem at Yucca Mountain will be subjected to EFFs from both near-term and longer-term climate changes in addition to heat from a hot repository. Advances are being made in comprehending climate change although much uncertainty remains. There seems to be an analogy between the conceptual and research approaches regarding ecosystem responses to climate change and to subsurface heat from a repository that should be capitalized on for the Yucca Mountain Project.

- A panel of experts would facilitate developing a study program for addressing long-term ecological potential that would be difficult to achieve otherwise. The breadth of experience on such a panel lends credibility to the findings. The results of a panel's review bears on the issue of how much research is enough when dealing with environmental impacts and ecosystem potential.

In closing, our preliminary analysis is leading us to believe that until empirical information to the contrary is available the scenario presented in Figure 2 at the end of this paper must be assumed. This argues strongly for an integrated approach to environmental assessment and performance assessment of the Yucca Mountain site. The unified concept of ecosystems as interactive functional networks combined with the resource-based approach seems promising for understanding ecosystem processes and future ecological potential in the context of the performance of a hot repository.

The State of Nevada encourages the Department of Energy (DOE) to convene an expert advisory group to guide the DOE with respect to the long-term potential of the ecosystem at Yucca Mountain and its consequences to repository performance.

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Figure 1

POSTULATED CLIMATE CHANGE TIME LINE INCLUDING
A HOT REPOSITORY SCENARIO
(not drawn to scale)

?????????	return to glacial conditions
8000 yrs.	global warming abates
3000 yrs.	subsurface peak temperature maintained
700 yrs.	peak subsurface temperature (2°-13°C)
300 yrs.	subsurface (6-7m) temperature increases
100 yrs.	air temperature increases another 2°C; additional ecosystem stress occurs
60 yrs.	substantial ecosystem stress occurs
40 yrs.	air temperature increases another 1°C
0 yrs.	air temperature has increased 1°C

Figure 2

POSTULATED EXTREME SCENARIO FOR ENVIRONMENTAL RESPONSES TO A HOT REPOSITORY AT YUCCA MOUNTAIN

1. Subsurface temperature and local climate are altered.

2. Vegetation is reduced and precipitation is increased.

3. Runoff and infiltration increase.

4. Erosion and bedrock exposure increase.

5. Vegetation is eliminated.

6. Erosion and infiltration are maximized.

7. **Would the performance of a repository be influenced?**