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ENVIRONMENTAL PERFORMANCE ASSESSMENT: A CASE STUDY OF AN EMERGING METHODOLOGY

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ABSTRACT

The emerging methodology of environmental performance assessment offers a potential means by which the future consequences of new technologies can be evaluated. A pilot effort to create a nuclear waste repository at Yucca Mountain, Nevada, however, has yet to adequately address biological and societal components of the environment that will evolve at the site following closure and abandonment of a repository. The nonphysical components of environmental systems cannot be ignored in performance assessment studies and are likely to be no more recalcitrant to analysis than physical components such as the geologic and hydrologic characteristics of a site. If environmental performance assessment is to contribute to understanding the risks and uncertainties associated with technologies like nuclear waste disposal, the methodology must address all components of environmental systems in a comprehensive and integrated manner. A methodology that recognizes only physical factors stands little chance of predicting the future outcome of actions that will affect the environment for thousands of years.

The rapid development and complexity of modern technology assure that decisions made by society will increasingly risk affecting environmental systems far into the future. This raises questions about how to deal with the long-term consequences of actions that may threaten generations to come. Nuclear waste disposal is the first of these dangers to come under wide scrutiny. It has been suggested that the manner in which this problem is approached could serve as a model for dealing with other long-term consequences of technological change [1, 2]. High-level nuclear waste poses a threat to the environment for thousands of years; steps are being taken by the United States Department of Energy (DOE) to dispose of the waste in deep geologic repositories meant to be reasonably safe

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for at least 10,000 years. The concept of geologic disposal of nuclear waste pursued by the DOE is based on a dual-barrier approach to waste isolation that involves an engineered barrier and a natural environmental barrier. Long-term containment and isolation of radionuclides primarily is to be accomplished by the environmental barrier, subsequent to a 300- to 1000-year period during which the engineered barrier in the form of a cladding and canister combination may have corroded and released the waste into the repository environment [3, 4]. Ultimate containment and isolation of radionuclides from the biosphere is primarily to be attained by virtue of the natural setting of the repository. Thus, geologic isolation in the United States will rely ultimately on a site's natural environmental characteristics and features to confine radioactive waste to the vicinity of the repository and therby protect future environmental systems and generations.

The environmental uncertainties posed by disposing of nuclear waste in geologic repositories are recognized in probabilistic, risk-based regulatory requirements, compliance with which is to be demonstrated through the use of performance assessment [4-7]. "Performance assessment" means an analysis that identifies the processes and events that could affect a repository setting, models the associated uncertainties, and evaluates potential consequences to the environment. As the major available tool for making informed decisions regarding repository siting and licensing [8], performance assessment is an aspect of the nuclear waste disposal issue most likely to serve as a model for how long-term aspects of technological development may affect future environmental systems. The emerging methodology of environmental performance assessment, as applied to geologic disposal of nuclear waste, is reviewed here.

GEOLOGIC DISPOSAL AND PERFORMANCE ASSESSMENT IN THE UNITED STATES

The U.S. program for geologic disposal of high-level nuclear waste is set forth by the Nuclear Waste Polity Act of 1982 (NWPA) and the 1987 amendments to the act. As amended, the act requires that Yucca Mountain, located adjacent to the Nevada Test Site in southwestern Nevada, be evaluated as a suitable natural setting for a repository. Before authorization can be granted by the Nuclear Regulatory Commission (NRC) for constructing the repository and licensing it for operation, an environmental performance assessment must be carried out to demonstrate that the environment is likely to be protected from migrating radionuclides for at least 10,000 years [4]. A performance assessment methodology does not exist. The assessment program being developed by the NRC and the DOE is at an early stage and requires considerable evolution before it can be applied in other than simple bounding calculations of radionuclide releases to the accessible environment [8]. Because the regulations do not spell out how performance assessment is to be carried out, there is a need for agreement within the United States nuclear waste program on the methodology to be applied, especially regarding establishment of probabilities for risk assessment [9].

Much of the work relative to performance assessment for the Yucca Mountain Project has concentrated on constructing scenarios for future environmental systems [10-12]. The principal focus of scenario development for the Yucca Mountain environment has been on aspects of the physical environment such as geohydrology, geochemistry, and rock characteristics that are to comprise the primary barrier to radioactive waste migration. Once the components of the physical system are understood, plausible events will be postulated that could influence specific components of the system and lead ultimately to breaching of the repository and release of wastes to the biosphere [10]. Table 1 lists the physical components of the natural environment system believed to be important to the Yucca Mountain site.

The DOE and NRC performance assessment program for a geologic repository is based on the assumption that the most likely route for radionuclides released from a repository to take to the accessible environment is via ground water [3, 7, 13, 14]. Consequently, emphasis has been placed on environmental processes and scenarios that could lead to breaching the repository and releasing nuclear wastes to ground water. Other modes of repository breaching and mechanisms of transport of waste to the biosphere such as extrusive magmatic activity and denudation of the natural overburden also are considered but generally to a

Table 1. Physical Processes and Events Being Considered in Assessing the Environmental Performance of the Yucca Mountain Site for 10,000 Years

Geohydrology and ground-water hydraulics [3, 10, 11, 12]
Geochemistry [3, 12]
Tectonics and faulting [3, 10, 11, 12]
Volcanism [3, 10, 11]
Rock properties (e.g., thermodynamics and strength) [10, 11]
Site geometry and geology (stratigraphy) [3]
Occurrence of mineral and energy resources [3, 10, 11, 12]
Dissolution of rocks [12]
Formation of inorganic colloids [12]
Erosion and denudation of overburden [3, 10, 11]
Climatic change [12]
Surface hydrology and flooding [12]

lesser extent than components of the environmental system that affect ground-water transport. This is evident from Table 1 which largely considers physical processes and events such as geohydrology, geochemistry, tectonics, rock dissolution, climatic change, and flooding that affect ground-water transport scenarios.

Table 2 lists the non-physical components of environmental systems that are being addressed for the Yucca Mountain site. The paucity of biological processes and events considered reflects the early stage of development of the environmental performance assessment concept. The only biological process considered has been microbial growth which has only recently been brought to the attention of researchers [12]. The hypothesis is that microbes naturally present in the host rock formation could render radionuclides more mobile and readily accessible to the environment. Some emphasis has been placed on human activities that might influence repository site performance, in particular on irrigation, intentional ground-water and climatic manipulation, and intrusion from resource exploration and mining [12]. War, sabotage, chemical waste disposal, and archeological exhumation have been discounted as potential influences on the future environmental performance of the Yucca Mountain site. For those societal factors considered, the emphasis has been on the likelihood of natural conditions and resources at the site being such that in the future an activity could occur. Thus, the likelihood of future society itself being such that an event might occur has not been addressed. For example, the possibility of human intrusion into a repository is based on the probability of extractible natural resources occurring at the site and not on the likelihood of the nature of a future society being such that resource exploration might or might not occur.

Scenarios under study for repository performance assessment are shown in Table 3. Hunter *et al.* describe the procedure as one of constructing event trees that depict the alternative courses that various processes could take [10]. The result is a hypothetical sequence of future events that might allow radionuclides to breach the natural barrier and escape from a repository. For both the engineered barrier and the natural barrier, the events, in combination with the rock types (e.g., welded tuff, alluvium, argillite) composing the natural barrier

Table 2. Non-Physical Processes and Events Being Considered in Assessing the Environmental Performance of the Yucca Mountain Site

Natural microbial activity [12]
Human intrusion in search of natural resources [3, 10, 11, 12]
Future irrigation [12]
Ground-water recharge or withdrawal [12]
Climate control [12]

Table 3. Scenarios Being Considered for Environmental Performance Assessment of the Yucca Mountain Site

Hydrological alterations, increased underground water flow, and water-table rise [10, 11, 12]
Formation of new ground-water discharge points [12]
Tectonic disturbance, faulting, and rock fracturing [3, 10, 11]
Alteration of rock properties and geochemical changes [10, 11, 12]
Advance of a dissolution front [3, 12]
Extrusive magmatic activity [3, 10, 11, 12]
Erosion and overburden denudation [3, 10, 11]
Climatic control or change [3]
Migration of inorganic colloids [12]
Accelerated natural microbial activity [12]
Human intrusion by exploratory drilling [3, 10, 11, 12]

at the Nevada Test Site and Yucca Mountain led initially to 21,000 scenarios [10]. These next were narrowed to 4,000 scenarios, only 400 of which were considered sufficiently probable to pursue in the performance assessment program for the Yucca Mountain site [11]. Currently, eighty-four different scenario sequences (grouped in seventeen categories) are being analyzed by the DOE Yucca Mountain Project. The environmentally-based categories, listed in Table 3, are used as a basis for further analysis of disruptive event and process scenarios for Yucca Mountain [12], and include both physical and non-physical environmental factors influencing site performance. Table 3 also displays scenarios analyzed for the NRC in a demonstration of a hypothetical performance assessment methodology for a nuclear waste repository [14]. In the demonstration the objective was to show for a simple, idealized case that, in conformity with regulations and standards [4-6], performance assessment can be used to predict transport of radionuclides from a repository to the accessible environment. The constraints that ultimately will be posed by data limitations and uncertainties were recognized in the numerous assumptions made [14]. Nonetheless it was concluded that when perfected performance assessment methodology could serve to evaluate and demonstrate environmental performance of a repository site.

The scenarios shown in Table 3 assume that ground water poses the most likely route by which the environment and humans could be exposed to radioactive wastes in the future. For example, the environmental standards [4-6] assume that the principal risk to future individuals would be very small except for the possibility that individuals one day might use ground water from the vicinity of a repository. This risk also was recognized by the National Academy of Sciences [13], which concluded that for a site like Yucca Mountain water resources probably would be limited in the future as they are now and consequently any water available at the site would most likely be used by future generations. Despite these concerns, no attention in the environmental performance assessment program for the DOE Yucca Mountain Project is being given to the likelihood of future societal factors at Yucca Mountain being such that ground water there would be used. Instead, the focus is on that gound water itself and the likelihood of radionuclides reaching the biosphere via that route during the next 10,000 years. Scenarios of this sort depend more on information on environmental events and processes like those shown in Table 1 than those in Table 2. This is because it is accepted that food chains, ways of life, and population distributions over 10,000 years, unlike geologic and hydrologic factors, cannot be usefully predicted over such long periods of time [5, 12]. As a consequence no serious attempt is being made in the United States repository program to understand biologic and societal factors with respect to future environmental systems and the intergenerational consequences of nuclear waste disposal.

Once events, processes, and plausible future scenarios are well-defined, probabilistic and deterministic models must be developed to perform the complex computations that will be necessary for analyzing possible interactions among climates, geohydrologic regimes, tectonic disturbances, volcanism, geochemical alterations, and resource exploration. The analytical models for the Yucca Mountain site [15, 16] are in a rudimentary stage of development and are limited by existing knowledge of the geologic and hydrologic environment [8]. The work will try to incorporate alternative conceptual models and mathematical structures into the environmental performance assessment. Significant progress in developing definitive models to predict the behavior of the physical environment at Yucca Mountain will require much new information on how the geologic and hydrologic systems function and interact. This level of understanding will come only after five to seven years of planned field studies at the site are completed by DOE [17]. In the interim, the performance assessment program will continue developing plausible scenarios for the Yucca Mountain environmental system.

SOME METHODOLOGICAL LIMITATIONS AND UNCERTAINTY

Many difficulties stand in the way of understanding the complex environmental processes at Yucca Mountain. As noted, the focus to date has been on understanding the nature of the physical system. The DOE has developed detailed plans to characterize the geologic and hydrologic environment at the site [17]. The efficacy of the performance assessment program depends on the ability of science to "interrogate" the site's environment successfully enough to warrant probabilistic and/or deterministic predictions of events and processes in at least the next 10,000 years. Several reviews have been undertaken of the ability of existing study methods and techniques to provide the data and information needed for constructing models of the Yucca Mountain geology and hydrology. For example, Jones, *et al.* found that seismic reflection profiling and electromagnetic methods are of little use in determining the deep internal geologic structure due to the complexity of the site [18]. It also was concluded that seismic refraction techniques require further development to overcome existing limitations with respect to Yucca Mountain's geology. Other efforts have found an absence of commonly agreed upon techniques and theory for characterizing and modeling ground-water movement in unsaturated fractured rock media like that at Yucca Mountain [19-21]. These findings for both the geologic and geohydrologic environment at the Yucca Mountain site were endorsed by an oversight review of the DOE Project [22].

Difficulties also exist with respect to understanding subsurface geochemistry and the combined radionuclide-fluid-rock interactions. Only now are preliminary efforts being made to model geochemical phenomena with respect to radionuclide transport and repository performance assessment. Many difficulties have arisen [23]. For example, it has recently come to light that colloids in the subsurface environment play an important role in the migration of radionuclides [23, 24]. Failure to account for colloidal movement can lead to significant underestimates of the distances that radionuclides will migrate in ground-water systems. McCarthy and Zachara discuss instances where waste plutonium and americium have, over short periods of time, unexpectedly traveled in excess of thirty miles below ground due to colloidal mechanisms, when laboratory analyzes indicated that movement of only a few millimeters would be expected [24]. The occurrence and properties of below-ground colloids are poorly understood, so the insights necessary for predictive modeling of this mode of transport are not well developed. Relevant to the Yucca Mountain site are concerns that colloids may be important to mobilizing radionuclides in both the vadose and the saturated ground-water zones. It is further suspected that in combination with naturally occurring microbes, biocolloids could be formed [24], which would further complicate understanding ground-water transport of radionuclides from a geologic repository to the accessible environment. This possibility would significantly complicate performance assessment for Yucca Mountain and emphasizes the uncertainties that exist with respect to biological components of the environmental system.

The complexity of Yucca Mountain's physical setting and the absence of reliable data, techniques, and models for predicting future tectonics, seismicity, volcanism, and geohydraulics that will govern transport of radionuclides from a geologic repository to the biosphere limits existing scientific and technological capabilities and results in considerable uncertainty with respect to performance assessment for the Yucca Mountain Project [19, 25]. Because of the long half-lives of radionuclides involved and the need to accurately predict their fates in the environment for at least 10,000 years, best or conservative estimates will not suffice. In the face of large uncertainties in characterizing the geology and geohydrology of a site like Yucca Mountain and the uncertainties inherent in long-term prediction it is imperative to quantify the uncertainties in predicting repository performance in order to establish levels of confidence in assessing the performance of a site [19]. This limitation was recognized conceptually in the NWPA and the applicable environmental radiation standards [4-6], and must be dealt with in the course of environmental performance assessment for the Yucca Mountain site. Consequently, considerable attention is now being devoted to the task of characterizing and analyzing probabilities and environmental uncertainties [19, 26].

Table 4 lists the broad classes of uncertainty that apply to a geologic repository site like Yucca Mountain. At this stage most attention is being devoted to the uncertainty related to the geosciences where the need for validated probabilistic and conceptual models is clearly recognized as being critical [19]. Some attention has been turned to the future state of the non-geologic environment in terms of predictions, probabilities, and uncertainties associated with future climate. This is critical not only to future hydrologic regime at a repository site but also to the biological and societal components of the environmental system that may develop there, possibly enhancing radionuclide accessibility to the environment. Unfortunately no definitive methods exist for predicting climates over thousands of years and no study has addressed all the environmental processes and events necessary to predict future conditions at the resolution needed for evaluating repository sites and conducting performance assessments [26].

Limited effort has been devoted to date to predictions and uncertainties associated with non-physical components of environmental systems (as in Table 2). In the United States repository program, human intrusion is considered one of the most likely of the occurrences that might compromise repository integrity [26]. Consequently, this possibility has been addressed somewhat,

Table 4. Types and Sources of Uncertainty that Apply to Environmental Performance Assessment for a Geologic Repository Site (Based on Buxton [19])

Variation in the natural environmental setting and choice of parameters
Conceptual and probabilistic modeling (definitions and calculations)
Future evolution of the environmental system (physical, biological, and societal)
Measurement errors (systematic, random, bias, arbitrary)

especially in the resource exploration scenario, which is particularly applicable to Yucca Mountain because the site is located in a region characterized by extractible mineral resources. Hunter and Mann concluded that objective estimates of the future mineral resource potential of an area cannot be made with known techniques [26].

Another human intrusion issue centers around the possibility of unintentional intrusion. Gillis reported on the findings of the DOE Human Interference Task Force [27], which evaluated modes of unintentional human intrusion into a nuclear waste repository. The study concluded that the probability of human intrusion could satisfactorially be reduced by using comprehensive communication systems at the repository site in the form of permanent markers. This conclusion was reached without the use of scenario, probability, or uncertainty analyses. Nonetheless, the results of the study have been used in the Yucca Mountain Project to largely dismiss the issue of human intrusion. Thus, this and other uncertainties associated with societal components of future environmental systems at Yucca Mountain are not being aggressively pursued.

Uncertainty also is introduced in environmental performance assessment of a repository site by errors associated with measuring environmental parameters. These can result from inaccurate instruments, inferences made from erroneous data, and from bias and arbitrariness introduced into assumptions made in data analysis and interpretation [19]. Crowe has recognized intentional bias built into the Yucca Mountain Project as a result of mounting pressure to "prove" the site in the face of increased funding and political realities [28]. This concern appears increasingly valid in light of the fact that Yucca Mountain represents the sole site being considered for a high-level nuclear waste repository in the United States. With no alternative to Yucca Mountain, the success of the DOE repository siting program rests on the correct assumption having been made that Yucca Mountain is an acceptable, licensable site.

As has been argued, at this stage in the environmental performance assessment program for the Yucca Mountain site, there seems to be little effort devoted to non-physical components of the environmental system in constructing future scenarios. Instead, there is a tacit assumption that biologic and societal factors cannot be usefully predicted [5, 12]. Rather than (say) trying to assess the likelihood of a future society taking some action at Yucca Mountain that will interfere with the performance of the natural environment as a barrier to radionuclide movement to the biosphere, the approach is to focus on the physical component of the environmental system that would be altered either by direct manipulation or as the indirect consequences of manipulation. Exploitation of the ground-water system as a water supply source is an example. As a result there is no attempt to construct and assess scenarios that embody plausible alternative courses of society and ecosystems that might develop at and affect the performance of the Yucca Mountain site in terms of nuclear waste isolation. Nowhere does there appear to have been a serious effort made to identify the sources of such uncertainty and consider how these uncertainties may be addressed or resolved by insights into future development of biological and societal components of environmental systems.

DISCUSSION AND CONCLUSIONS

The extent of information and analysis needed to carry out a 10,000-year environmental performance assessment is immense, on a scale never before attempted, and challenges the ability of science to comprehend the complexities and uncertainties involved. This is particularly true when the comprehensive physical, biological, and societal nature of environmental systems is considered. The importance of societal components of environmental systems to the integrity of a repository system was considered in part by the Swedish National Board for Spent Nuclear Fuel [1], which recognized that the nuclear waste issue may become a model for dealing with long-term consequences of other technologies. Their study found it essential to the success of the Swedish geologic repository program that means be sought for addressing risks and uncertainties from societal components of the environmental system. Similarly, the Canadian Nuclear Fuel Waste Management Program considers biosphere modeling essential for estimating the range and probabilities of environmental effects of geologic disposal of nuclear wastes [29].

In the performance assessment program for the Yucca Mountain site it is understandable that initial attention would be given to aspects of the physical environment such as those in Table 1. Not only are events and processes involving geologic and hydrologic factors easier to portray than those involving biological and societal ones, but the non-physical factors appear more likely to pose limits to the site's ability to perform as required and isolate nuclear wastes for at least 10,000 years. Soon, however, the more difficult task of identifying and understanding non-physical events, processes, and scenarios that could characterize future environmental systems at Yucca Mountain must be undertaken. The importance of this is underscored by postulated scenarios [5, 13], suggesting that the distant future use of ground water from the vicinity of a repository in an arid region like southwestern Nevada could result in substantial health risks to individuals. These preliminary analyses were based on limited information on ground-water travel time, radionuclide migration, the assumption that water will continue to be limited in the distant future, and the further assumption that, as is the case now in the Yucca Mountain region, ground water will be used by humans for potable water and irrigation. Thus, the generally arid nature of the Yucca Mountain site suggests that potentially contaminated ground water is likely to be used and that individual radioactive dose rate criteria may not be met [13].

Another example of the need to address future societal scenarios concerns inadvertent human intrusion. Efforts to date have focused only on means of marking a repository so that future generations would detect and avoid or manage its hazards [27]. In the same light it bears noting that lack of a means of assessing the potential of a future society to explore a given site for natural resources led only to the simplistic recommendation that a repository not be sited where any natural material occurs in greater abundance that the average for the Earth [26].

While uncertainties with respect to the physical environment may be dealt with separately in the initial stage of an environmental performance assessment for a repository, the large uncertainties posed by biological and societal factors cannot be set aside without further consideration. Within the various scenarios analyzed for Yucca Mountain must be what really will occur at the site during the next 10,000 years. Otherwise, the entire performance assessment exercise will be for naught, despite the sophistication of the analytical methodologies used. Incorrect scenario specification may result in a nuclear waste repository not performing as intended. It has been pointed out that incorrect specification of repository performance scenarios is likely to be the most significant source of error in trying to assess how the environmental system will behave [19].

There is some reason to believe that currently perceived limitations to dealing with the uncertainties posed by non-physical factors can be overcome. Recent applications of risk and uncertainty analyses to environmental assessment holds the promise of quantifying biological and societal factors [30, 31]. Adequate knowledge of the non-physical components of the environment seems to exist. The constraints that remain to successful application of risk and uncertainty analyses to them appear to be:

1. Adapting existing models to express output in terms of probabilities; and
2. Expressing data in terms that allow uncertainties to be quantified.

A category of recently developed computer programs referred to as "expert systems" also may help overcome some of the limitations of traditional assessments based on subjective judgement. For example, Lein has argued that expert systems encoded with the knowledge of biological and societal factors affecting the course of a future technology can provide solutions to specialized problems previously thought not to be amenable to more traditional risk and uncertainty analysis [32]. Prototype expert systems appear to suggest that artificial intelligence can be used to screen comprehensive alternative scenarios reflecting both physical and non-physical events and processes. If so, it is possible that tools may soon exist for evaluating and assessing the importance of cultural, societal, and other non-physical factors in environmental systems. Certain parameters that can be documented, characterized, compared over time, and used to predict trends have been identified [33, 34]. Conceptual means of formulating these issues are available [35], as are the rudiments of an information base [36]. New ways of addressing heretofore unmanagable issues within performance assessment models thus may be within reach. This suggests that uncertainties posed by biological and societal factors may be no greater and no more recalcitrant to resolution that those associated with the physical aspects of environmental systems. They simply are receiving less attention than geologic, hydrologic, and related factors in the United States repository program.

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