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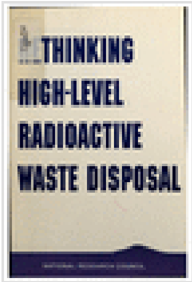

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RETHINKING HIGH-LEVEL RADIOACTIVE WASTE DISPOSAL

A Position Statement of the Board on Radioactive Waste Management

Commission on Geosciences, Environment, and Resources
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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ABSTRACT

There is a worldwide scientific consensus that deep geological disposal, the approach being followed in the United States, is the best option for disposing of high-level radioactive waste (HLW). There is no scientific or technical reason to think that a satisfactory geological repository cannot be built. Nevertheless, the U.S. program, as conceived and implemented over the past decade, is unlikely to succeed.

For reasons rooted in the public's concern over safety and in the implementing and regulatory agencies' need for political credibility, the U.S. waste disposal program is characterized by a high degree of inflexibility with respect to both schedule and technical specifications. The current approach, in which every step is mandated in detail in advance, does have several advantages:

- it facilitates rigorous oversight and technical auditing;
- its goals and standards are clear;
- it is designed to create a sense of confidence in the planning and operation of the repository; and
- if carried out according to specifications, it is robust in the face of administrative or legal challenge.

This approach is poorly matched to the technical task at hand. It assumes that the properties and future behavior of a geological repository can be determined and specified with a very high degree of certainty. In reality, however, the inherent variability of the geological environment will necessitate frequent changes in the specifications, with resultant delays, frustration, and loss of public confidence. The current program is not sufficiently flexible or exploratory to accommodate such changes.

The Board on Radioactive Waste Management is particularly concerned that geological models, and indeed scientific knowledge generally, have been inappropriately applied. Computer modeling techniques and geophysical analysis can and should have a key role in the assessment of long-term repository isolation. In the face of public concerns about safety, however, geophysical models are being asked to predict the detailed structure and behavior of sites over thousands of years. The Board believes that this is scientifically unsound and will lead to bad engineering practice.

The United States appears to be the only country to have taken the approach of writing detailed regulations before all of the data are in. As a result, the U.S. program is bound by requirements that may be impossible to meet. The Board believes, however, that enough has been learned to formulate an approach that can succeed. This alternative approach emphasizes flexibility:

SUMMARY

Since 1955, the National Research Council (NRC) has been advising the U.S. government on technical matters related to the management of radioactive waste. Today, this advice is provided by the Board on Radioactive Waste Management (BRWM or "the Board"), a permanent committee of the NRC. The conclusions presented in this position statement are the result of several years of discussions within the Board, whose members possess decades of professional experience in relevant scientific and technical fields.

In July 1988, the Board convened a week-long study session in Santa Barbara, California, where experts from the United States and abroad joined BRWM in intensive discussions of current U.S. policies and programs for high-level radioactive waste (HLW) management. The group divided its deliberations into four categories: (1) the limitations of analysis; (2) moral and value issues; (3) modeling and its validity; and (4) strategic planning. A summary of the findings of these discussions, from which this position statement has been developed, follows the Summary.

Current U.S. Policy and Program

In the Nuclear Waste Policy Act of 1982 (NWPA), Congress assigned responsibility to the Department of Energy (DOE) for designing and eventually operating a deep geological repository for high-level radioactive waste. The repository must be licensed by the U.S. Nuclear Regulatory Commission (USNRC) and must meet radionuclide release limits, based on a generic repository, that would result in less than 1000 deaths in 10,000 years as specified in a Standard established by the Environmental Protection Agency (EPA) (40 CFR 191).

The U.S. program is unique among those of all nations in its rigid schedule, in its insistence on defining in advance the technical requirements for every part of the multibarrier system, and in its major emphasis on the geological component of the barrier as detailed in 10 CFR 60. Because one is predicting the fate of the HLW into the distant future, the undertaking is necessarily full of uncertainties. In this sense the government's HLW program and its regulation may be a "scientific trap" for DOE and the U.S. public alike, encouraging the public to expect absolute certainty about the safety of the repository for 10,000 years and encouraging DOE program managers to pretend that they can provide it.

For historical and institutional reasons, DOE managers tend to feel compelled to do things perfectly the first time, rather than to make changes in concept and design as unexpected geological features are encountered and as scientific understanding develops. This "perfect knowledge" approach is unrealistic, given the inherent uncertainties of this unprecedented undertaking, and it runs the risk of encountering "show-stopping" problems and delays that could lead to a further deterioration of public and scientific trust. Today, because of the regulatory requirements and the way the program is being carried out, U.S. policy has not led to satisfactory progress on the problem of radioactive waste disposal.

Scientific Consensus on Geological Isolation

There is a strong worldwide consensus that the best, safest long-term option for dealing with HLW is geological isolation. High-level waste should be put into specially designed and engineered facilities underground, where the local geology and groundwater conditions have been chosen to ensure isolation of the waste for tens of thousands of years or longer, and where waste materials will migrate very slowly if they come into contact with the rock.

Although the scientific community has high confidence that the general strategy of geological isolation is the best one to pursue, the challenges are formidable. In essence, geological isolation amounts to building a mine in which "ore" will be put back into the ground rather than taken out. Mining, however, has been and remains fundamentally an exploratory activity: because our ability to predict rock conditions in advance is limited, miners often encounter surprises. Over the years, mining engineers have developed methods to deal with the vagaries of geological environments, so that mineral extraction and construction can continue safely even when the conditions encountered are different from those anticipated.

It is at this point that geological isolation of radioactive waste differs in an important sense from mining. In the United States, radioactive waste management is a tightly regulated activity, surrounded by laws and regulations, criteria and standards. Some of these rules call for detailed predictions of the behavior of the rock for the tens of thousands of years that the radioactive materials are to be isolated.

Preparing quantitative predictions so far into the future stretches the limits of our understanding of geology, groundwater chemistry and movement, and their interactions with the emplaced material (radioactive waste package, backfill, sealants, and so forth). Although the basic scientific principles are well known, quantitative estimates (no matter how they are obtained) must rely on many assumptions. As a consequence, the resulting estimates are uncertain to some degree, and they will remain uncertain no matter how much additional information is gathered.

Treatment of Uncertainty

The character and implications of these uncertainties must be clearly understood by political leaders, program managers, and the concerned public. Engineers and scientists, no matter how experienced or well trained, are unable to anticipate all of the potential problems that might arise in trying to site, build, and operate a repository. Nor can science "prove" (in any absolute sense) that a repository will be "safe" as defined by EPA standards and USNRC regulations. This is so for two reasons.

First, proof in the conventional sense cannot be available until we have experience with the behavior of an engineered repository system—precisely what we are trying to predict. The existence of uncertainties has prompted efforts to improve the technical analysis, but there will always remain some residual uncertainty. It is important to recognize, however, that uncertainty does not necessarily mean that the risks are significant. What it does mean is that a range of results are possible, and a successful management plan must accommodate residual uncertainties and still provide reasonable assurance of safety.

Second, safety is in part a social judgment, not just a technical one. How safe is safe enough? Is it safer to leave the waste where it is, mostly at reactor sites, or to put it in an underground repository? In either case safety cannot be 100 percent guaranteed. Technical analyses can provide background for answering such questions, but ultimately the answers depend on choices made by the citizens of a democratic society. The EPA has not based its standards (which must allow for these choices by the citizenry) on social judgments derived from realistic consideration of these alternatives. Both of these important limitations of the analysis have been understated.

The federal government must provide full public accountability as information about the risks changes with experience. This is not an impossible task: government and business make decisions every day under similar conditions of uncertainty. But a policy that promises to anticipate every conceivable problem, or assumes that science will shortly provide all the answers, is bound to fail.

The public has been told too often that absolute guarantees can be provided, but most citizens watching the human frailties of their governments and technologists know better. A realistic—and attainable—goal is to assure the public that the likelihood of serious unforeseen events (serious enough to cause catastrophic failure in the long term) is minimal, and that the consequences of such events will be limited. These assurances rest on the credible application of general principles, rather than a reliance on detailed predictions.

Modeling of Geological Processes

The current U.S. approach to developing a geological repository (with a mandated 10,000-year lifetime) for radioactive waste is based on a regulatory philosophy that was developed from the licensing of nuclear power plants (which have a nominal 40-year lifetime). The geological medium, however, cannot be specified in advance to the degree possible for man-made components, such as valves or electronic instruments, nor can it be tested over its projected lifetime as can many man-made components. Commercial mining and underground construction both operate on the sound principle of "design (and improve the design) as you go." The inherent variability of the geological environment necessitates changes in specifications as experience increases. If that reality is not acknowledged, there will be unforeseen delays, rising costs, frustration among field personnel, and loss of public confidence in the site and in the program.

Models of the repository system are useful, indeed indispensable. The computerized mathematical models that describe the geological structure and hydrological behavior of the rock are needed to manage the complex calculations that are necessary to evaluate a proposed site. Models are vital for two purposes: (1) to understand the history and present characteristics of the site; and (2) to predict its possible future behavior. Putting the available data into a coherent conceptual framework should focus attention on the kinds of uncertainty that persist. For example, the modeling of groundwater flow through fractured rock lies at the heart of understanding whether and how a repository in hard rock will perform its essential task of isolating radioactive materials. The studies done over the past two decades have led to the realization that the phenomena are more complicated than had been thought. Rather than decreasing our uncertainty, this line of research has increased the number of ways in which we know that we are uncertain. This does not mean that science has failed: we have learned a great deal about these phenomena. But it is a commonplace of human experience that increased knowledge can lead to greater humility about one's ability to fully understand the phenomena involved.

Uncertainty is treated inappropriately in the simulation models used to describe the characteristics of the waste repository. As the quantity of information about natural geological settings grows, so too does our appreciation of their variability and unpredictability. This distinction has often been ignored. Indeed, the very existence of large databases and sophisticated computer models suggests, erroneously, that it is appropriate to design a geological repository as if it were a nuclear power plant or jet airliner, both of which have predictable attributes over their short lifetimes. That assumption of accurate predictability will continue to produce frustration and failure. Under the present program models are being asked to provide answers to questions that they were not designed to address. One scientifically sound objective of geological modeling is to learn, over time, how to achieve reasonable assurance about the long-term isolation of radioactive waste. That objective is profoundly different from predicting quantitatively the long-term behavior of a repository. Yet, in the face of public concerns about the safety of HLW disposal, it is the latter use to which models have been put.

The Board believes that this use of geological information and analytical tools—to pretend to be able to make very accurate predictions of long-term site behavior—is scientifically unsound. Its conclusion is based on detailed reviews of the methods used by the DOE and the regulatory agencies in implementing the NWPA.

Well-known geophysical principles can be used to estimate or to set bounds on the behavior of a site, so that its likely suitability as a waste repository can be evaluated. But it is inappropriate to stretch the still-incomplete understanding of a site into a quantitative projection of whether a repository will be safe if constructed and operated there. Only after a detailed and costly examination of the site itself can an informed judgment be reached, and even then there will still be uncertainties.

Many of the uncertainties associated with a candidate repository site will be technically interesting but irrelevant to overall repository performance. Further, the issues that are analytically tractable are not necessarily the most important. The key task for performance modeling is to separate the significant uncertainties and risks from the trivial. Similarly, when there are technical disputes over characteristics and processes that affect calculations of waste transport, sensitivity analysis with alternative models and parameters can indicate where further analysis and data are required and where enough is known to move on to other concerns.

It may even turn out to be appropriate to delay permanent closure of a waste repository until adequate assurances concerning its long-term behavior can be obtained through continued in-site geological studies. Judgments of whether enough is known to proceed with placement of waste in a repository will be needed throughout the life of the project. But these judgments should be based on a comparison of available alternatives, rather than a simplistic debate over whether, given current uncertainties, a repository site is "safe." Even while the detailed, long-term behavior of an underground repository is still being studied, it may be marginally safer to go ahead and store reactor waste there (in a way that permits retrieval if necessary), rather than leaving it at reactors.

As a rule, the values determined from models should only be used for comparative purposes. Confidence in the disposal techniques must come from a combination of remoteness, engineering design, mathematical modeling, performance assessment, natural analogues (see below), and the possibility of remedial action in the event of unforeseen events. There may be political pressure on implementing agencies to provide absolute guarantees, but a more realistic—and attainable—goal is to assure the public that the likelihood of unforeseen events is minimal, and that the magnitude of the consequences of such events is limited. Such an alternative approach, now being used in Canada and Sweden, promises to be far more successful in achieving a safe and practical waste disposal system.

Moral and Ethical Questions

Radioactive waste poses hazards that raise moral and ethical concerns. First, some of the radioactivity lasts for extremely long periods of time—the EPA standard for HLW calls for isolation of the waste for 10,000 years and more, a time longer than recorded human history. Second, the risks of high-level waste will be concentrated at a very few geological repositories. The neighbors of proposed waste repositories have understandably been alarmed at the prospect of hosting large quantities of a material that needs to be handled with great care. Ethical studies in this area underscore two points: (1) the central role of a fair process; and (2) the pervasive problem of promising more certainty than can be delivered.

The need for a fair process is simply stated: people feel threatened by radioactive waste; and they deserve to be taken seriously in the decision-making process. The sense of threat is often ill informed, in a narrow technical sense; but when that occurs, it is the duty of technical experts and program managers to provide information and employ analyses that will be credible to the affected populations. Only with valid information that they believe can those affected parties negotiate equitable solutions. The primary goal of the program is to provide safe disposal; a secondary goal is to provide it without any gross unfairness. As a result, the mechanisms of negotiation, persuasion, and compensation are fundamental parts of any program to manage and dispose of radioactive waste—not mere procedural hoops through which program managers must jump.

The second ethical point is also important: the demand for accountability in our political system has fostered a tendency to promise a degree of certainty that cannot be realized. Pursuing that illusory certainty drives up costs without delivering the results promised or comparable benefits. The consequence is frustration and mistrust. For example, it is politically costly to admit that one has been surprised in exploring sites being considered for HLW repositories. Yet, this situation is self-defeating: surprises are bound to occur because a principal reason for exploration is to discover what is there.

Instead of pursuing an ever-receding mirage, it is sensible to pursue an empirical exploratory approach: one that emphasizes fairness in the process while seeking outcomes that the affected populations judge to be equitable in light of their own values. This is not an easy course, but it is necessary.

An Alternative Approach

There are scientific reasons to think that a satisfactory HLW repository can be built and licensed. But for the reasons described earlier, the current U.S. program seems unlikely to achieve that desirable goal. The Board proposes an alternative approach that is built on well-defined goals and objectives, utilizes established scientific principles, and can be achieved in stages with appropriate review by regulatory and oversight bodies and with demonstrated management capabilities. The Board suggests an institutional approach that is more flexible and experimental—in other words, a strategy that acknowledges the following premises:

- Surprises are inevitable in the course of investigating any proposed site, and things are bound to go wrong on a minor scale in the development of a repository.
- If the repository design can be changed in response to new information, minor problems can be fixed without affecting safety, and major problems, if any appear, can be remedied before damage is done to the environment or to public health.

This flexible approach can be summarized in three principles:

- Start with the simplest description of what is known, so that the largest and most significant uncertainties can be identified early in the program and given priority attention.
- Meet problems as they emerge, instead of trying to anticipate in advance all the complexities of a natural geological environment.
- Define the goal broadly in ultimate performance terms, rather than immediate requirements, so that increased knowledge can be incorporated in the design at a specific site.

In short, this approach uses a scientific approach and employs modeling tools to identify areas where more information is needed, rather than to justify decisions that have already been made on the basis of limited knowledge.

The principal virtue of this strategy is that it would use science in the proper fashion. It would be similar to the strategies now being followed in Canada and Sweden, where the exploration and construction of an underground test laboratory and a shallow underground low-level waste repository have followed a flexible path. At each step, information and understanding developed during the prior stages are combined with experience from other underground construction projects, in order to modify designs and procedures in light of the growing stock of knowledge. During operations and after closure of the facilities, the emphasis will be on monitoring and assuring the capability to remedy unforeseen problems. In that way, the possibility is minimized that unplanned or unexpected events will compromise the integrity of the facility.

This flexible approach has more in common with research and underground exploration than with conventional engineering practice. The idea is to draw on natural analogues, integrate new data into the expert judgments of geologists and engineers, and take advantage of favorable surprises or compensate for unfavorable ones.

Natural analogues—geological settings in which naturally occurring radioactive materials have been subjected to environmental forces for millions of years—demonstrate the action of transport processes like those that will affect the release of man-made radionuclides from a repository in a similar setting. Where there is scientific agreement that the analogy applies, this approach provides a check on performance assessment methodology and may be more meaningful than sophisticated numerical predictions to the lay public.

A second element is to use professional judgment of technical experts as an input to modeling in areas where there is uncertainty as to parameters, structures, or even future events. Such judgments, which may differ from those of DOE program managers, should be incorporated early in the process; a model created in this way might redirect the DOE program substantially.

The large number of underground construction projects that have been completed successfully around the world are evidence that this approach works well. Implicit in this approach, however, is the need to revise the program schedule, the repository design, and the performance criteria as more information is obtained. Putting such an approach into effect would require major changes in the way Congress, the regulatory agencies, and DOE conduct their business.

The Risk of Failing to Act

Given the history of radioactive waste management in the United States, a likely alternative is that the program will continue as at present. That would leave the nation's inventory of high-level waste, indefinitely, where it is now: mostly at reactor sites at or near the earth's surface. By the year 2000, spent fuel is expected to contain more than 3×10^{10} curies, while High Level Waste is expected to contain another 10^9 curies.* This alternative is safe in the short term—on-site storage systems are safe for at least 100

*Integrated Database for 1988: Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics: DOE/RW-0006 Revision 4, Sept. 1988.

years, according to present evidence.* The at-surface alternative may be irresponsible for the long run, however, due to the uncertainties associated with maintaining safe institutional control over HLW at or near the surface for centuries.

In judging disposal options, therefore, it is essential to bear in mind that the comparison is not so much between ideal systems and imperfect reality as it is between a geologic repository and at-surface storage. From that standpoint, both technical experts and the general public would be reassured by a conservative engineering approach toward long-term safety, combined with an institutional structure designed to permit flexibility and remediation.

*Waste Confidence Decision Review. 54 FR 39767 (Sept. 28, 1989)

INTRODUCTION

The Origins and Purpose of This Document

Since 1955, the National Research Council (NRC) has been advising the U.S. government on technical matters related to the management of radioactive waste. Today, such review and advice is rendered by the Board on Radioactive Waste Management (BRWM or "the Board"), a permanent committee of the National Research Council. Over the past quarter century, the BRWM and its predecessors have acted as observer, critic, and adviser to the federal agencies responsible for the management of radioactive waste. In 1955, the National Research Council's Committee on Earth Sciences, the forerunner of the BRWM, first examined the problem of high-level radioactive waste (HLW) and recommended the strategy of isolation in stable geological formations. That basic approach is the one still being pursued in the United States and throughout the world. In 1983, the Board published the report of its Waste Isolation Systems Panel, a technical document that supported the use of "performance assessment." This method, first employed by the Karnbranslesakerhet (KBS) in Sweden for judging the performance of high-level waste and its packaging in geological formations, makes it possible to evaluate the ability of a repository to contain waste for the very long term. Performance assessment has become the keystone of the policies and regulations guiding the planning of HLW disposal in the United States as well as other nations.

Thus far, however, the technical programs carried out by government and industry in the United States have not led to a socially satisfactory resolution of the problem of HLW management and disposal. There are two reasons for this failure.

The first is the controversy over nuclear energy and radioactive waste disposal as part of nuclear energy development. The Board takes no position on the use of nuclear energy. However, it notes that even if nuclear power in this country were discontinued tomorrow—a highly unlikely event—we would still need to dispose of nuclear waste from existing power plants and defense programs, and we would therefore still require a viable HLW disposal program.

The second reason that radioactive waste management remains in trouble is the way in which the programs have been designed and carried out. That problem is the subject of this report: the Board believes that important scientific and technical issues concerning HLW have been widely misunderstood; the result is a set of programs that will not achieve their stated goals. Neither the technical nor the social problems of the waste materials already in existence are being handled effectively. The Board believes that the safe and effective isolation of radioactive waste is feasible. Improvements to what is now being done are described below.

These conclusions are the result of several years of discussions within the Board and are based on the decades of scientific and professional experience represented among the members of the BRWM. In July 1988 the Board convened a week-long study session in Santa Barbara, California, where the Board was joined by experts from the United States and abroad. The group divided its deliberations into four categories: (1) the limitations of analysis; (2) moral and value issues; (3) modeling and its validity; and (4) strategic planning. These categories also determine the structure of this position statement, although in the analysis here, as in the real world, there is no easy separation among them.

Although this position statement is critical of present policies, it must be emphasized that the changes that need to be made are not restricted to the U.S. government. The nature of the risks and the government's responsibility to address them need to be presented and understood in terms different from those reflected in today's public policy. Doing so will not lead to less safety but to more. Yet achieving that result will require courage on the part of leaders in government and industry, as well as a willingness to rethink risks among the public at large and in the interest groups concerned with public policies for the management of risk.

These questions touch on far more than radioactive waste, and the re-thinking they imply will be difficult to launch and to sustain. The Board believes, however, that this rethinking is essential and that radioactive waste management is a reasonable place to begin. This position statement is a step in that direction.

High-Level Waste in Context

At present, approximately 17 percent of the world's electricity is derived from about 400 nuclear power plants, although the percentage is as high as 70 percent in France and 50 percent in Sweden. The challenge of HLW disposal is dominated by the spent fuel from these nuclear power plants. Each 1,000-megawatt (MWE) nuclear power plant produces each year about 30 tons of spent fuel, which if reprocessed and vitrified could be reduced to between 4 and 11 cubic meters (m^3) of highly radioactive glass. Some countries, including the United States, have chosen to dispose of commercial spent fuel directly. Each power plant also produces some 400 m^3 of short-lived, low-level waste (LLW) each year. Fuel production would leave another 86,000 tons of mill tailings on the earth's surface for each reactor, per year.

Radioactive Waste Management Policy

Because HLW must be isolated from the living environment for 10,000 years or more, all nations faced with the task of radioactive waste disposal have chosen underground repositories as the basic technical approach. In the United States, the Department of Energy (DOE) has been given the task of designing and eventually operating such a repository. Before operations begin, however, DOE must demonstrate to the U.S. Nuclear Regulatory Commission (USNRC) that the repository will perform to standards established by the U.S. Environmental Protection Agency (EPA) that limit the release of radionuclides to specific levels for 10,000 years after disposal. Before the USNRC will grant a license to operate a repository, DOE must present convincing data and analysis to the USNRC showing that the proposed facility can meet specified release limits.

To develop such an assessment, it is necessary to examine all credible possibilities for the movement of radionuclides from the repository and into the accessible environment. In conducting these analyses, DOE has relied heavily on building computer models of the repository and surrounding geological environment, along with possible pathways of radionuclide transport. However, preparing quantitative predictions so far into the future pushes the boundaries of our understanding of geology, groundwater chemistry and movement, and their interactions with the emplaced material (radioactive waste package, backfill, sealants, and so on). Although the basic scientific principles are well known, quantitative estimates (no matter how they are obtained) must rely on many assumptions. The resulting estimates cover a range of outcomes.

While continued scientific investigations should reduce the uncertainty, absolute certainty cannot be achieved. Indeed, a major theme of this position statement is the need for public policy to benefit from, and change in response to, accumulating experience.

FINDINGS

The Limitations of Analysis

Overview

Engineers are unable to anticipate all of the potential problems that might arise in trying to site, build, and operate a repository. Nor can science prove that a repository will be absolutely "safe." This is so for two reasons. First, proof in the conventional sense cannot be available until we have experience with the behavior of an engineered repository system—precisely what we are trying to predict ahead of time. And second, safety is in part a social judgment, not just a technical one. While technical analyses can greatly illuminate the judgment of whether a repository is safe, technical analysis alone cannot substitute for decisions about the degree of risk that is acceptable. These decisions belong to the citizenry of a democratic society. Both of these important limitations of technical analysis have been understated, a lapse that feeds the concern and magnifies the public's distrust of nuclear waste managment when these limitations are pointed out by the program's critics.

Uncertainty and Significant Risks

A principal source of concern over the U.S. program is the uncertainty in estimating the risks from a radioactive waste repository. Technical approaches are available to reduce or at least bound these uncertainties. Yet in focusing on ways to improve the analysis, public discussion has often overlooked a more important question: whether the uncertainty matters. This is, in principle, the domain of performance assessment, which draws together the different portions of the technical analysis so that one can see which parts of the waste confinement system may pose environmental hazards during or after the time when the repository receives waste.

Performance assessment of a repository system is necessarily a task for computer modeling. The waste management system, which starts at the reactor and continues into the distant future of a sealed repository, includes many different parts and processes that are described through different kinds of data (with different levels of quality), and different kinds of analysis (with different levels of accuracy). It is a practical consequence of the complexity of high-level radioactive waste (HLW) disposal, together with the fact that no one has ever operated a repository, that performance assessment is, in the end, a matter of technical judgment.

The traditional approach in such cases, where an important social decision hinges on uncertain scientific data and projections, is to inform the political decision through a consensus of the appropriate technical community. Such consensus is difficult to reach in this case, however, given the political controversy, conflicting value systems, and overlapping technical specialties involved in assessing repository performance. Indeed, the allowable residual risk associated with a permissible repository site is a political choice; EPA has taken the position that the implementation of their guidelines constitutes the exercise of this choice. Unfortunately, the number and magnitude of the uncertainties in the probabilistic approach may be expected to reintroduce political controversy. This was recognized by the High-Level Radioactive Waste Disposal Subcommittee of EPA's Science Advisory Board in their January 1984 report reviewing EPA Draft Standard 40 CFR 191. That subcommittee concluded there was

> insufficient basis for agreeing with the EPA staff that the proposed release criterion with its probabilistic corollary can be demonstrated to have been met with reasonable assurance, and that this could be argued definitively in a legal setting.

The subcommittee strongly affirmed the validity of EPA's probabilistic approach, but warned that

> if EPA cannot have high confidence in the adequacy and workability of a quantitative, probabilistic standard, [it should] use qualitative criteria, such as recommended by [the US]NRC.

Specifically, with regard to the first major topic of the Science Advisory Board's findings and recommendations, "Uncertainty and the Standard," the subcommittee recommended relaxing the nuclide release limits by a factor of 10, modifying the probabilistic release criteria so that

> analysis of repository performance shall demonstrate that there is less than a 50% chance of exceeding the Table 2 release limits, modified as is appropriate. Events whose median frequency is less than one in one-thousand in 10,000 years need not be considered,

and, finally

> that use of a quantitative probabilistic condition on the modified Table 2 release limits be made dependent on EPA's ability to provide convincing evidence that such a condition is practical to meet and will not lead to serious impediments, legal or otherwise, to the licensing of high-level-waste geologic repositories. If such evidence cannot be provided, we recommend that EPA adopt qualitative criteria, such as those suggested by the [US]NRC.[1]

Unfortunately none of these recommendations was adopted.

The USNRC staff, in commenting on the EPA Draft Standard, strongly questioned the workability of quantitative probabilistic requirements for the defined releases stating, in part

> numerical estimates of the probabilities or frequencies of some future events may not be meaningful. The [US]NRC considers that identification and evaluation of such events and processes will require considerable judgment and therefore will not be amenable to quantification by statistical analyses without the inclusion of very broad ranges of uncertainty. These uncertainty ranges will make it difficult, if not impossible, to combine the probabilities of such events with enough precision to make a meaningful contribution to a licensing proceeding.[2]

The problem is compounded when the adequacy of the performance assessment—to determine if the allowable residual risk is achieved—is judged by its political impact (i.e., the effect of reopening the discussion of what is allowable residual risk) as well as its technical accuracy.

The difficulty of evaluating performance assessments is compounded by the fact that there is no actual experience in the disposal of HLW on which to base estimates of the risk. Some risk scenarios include low-probability/high-consequence events. Others are based on explicit or implicit assumptions that cannot be plausibly proved or disproved—for example, the consequences of climatic changes that could increase rainfall and groundwater flows at a repository site. The data and methodologies for modeling of repository isolation performance are still under development.

The actual performance of a repository is difficult to predict for many reasons. Geologists often disagree about the interpretation of data in analyzing the history of a site or geological structure. Long-term predictions are even more uncertain. Releases may occur thousands of years in the future, and they are likely to be diffuse and hard to detect. The potential for (and effects of) human exposure will be further shaped by unpredictable changes in demographics and technology.

These uncertainties do not necessarily mean that the risks are significant, nor that the public should reject efforts to site the repository. Rather, they simply mean that there are certain irreducible uncertainties about future risk. An essential part of any successful management plan is how to operate with large residual uncertainties, and how to maintain full public accountability as information about the risks changes with experience. This is not an impossible task: public policy is made every day under these conditions, and private firms undertake all sorts of activities in the face of uncertainty.

What is clear, however, is that a management plan that promises that every problem has been anticipated, or assumes that science will provide all the answers, is almost certainly doomed to fail. There have been many cases where attempts to understate uncertainty have damaged an agency's credibility and subverted its mission. For this reason, experienced regulatory agencies like EPA now pay careful attention to describing the uncertainties associated with their risk assessments.

Perceptions of Risk

Studies have linked the high public perceptions of the risk from nuclear power plants to certain qualities of that risk, in particular to perceptions that the risks are catastrophic, new, uncertain, and involuntary (i.e., beyond individual control). Radioactive waste poses risks with many of the same technical characteristics: the principal health risks (chiefly cancer and genetic defects) originate in the hazards of ionizing radiation. The risks from radioactive waste also have some of the same social characteristics as risks from nuclear reactors: a long time may pass before the hazards become apparent, dangers may be imposed involuntarily on populations, and there is a perceived possibility of catastrophe. The last perception, in particular, is qualitatively incorrect for HLW, since radioactive waste materials have far lower energy levels in comparison to those of reactors, thereby limiting the risk associated with HLW to much lower levels in virtually all accident scenarios.

Given the complexity of the potential risks from HLW, most people will transfer the judgment of the safety of geologic disposal to the experts. The key question is which experts they will listen to. The answer depends on who seems more trustworthy: citizens may have little experience with radioactive waste, but they have considerable experience in evaluating people.

The perception of integrity and competence in risk managers depends not only on their personal attributes but also on the character of the policies they implement and the institutions they represent. The current decision process is structured in a way that does not promote trust in those who are implementing the waste management program. The current situation in Nevada, for example, demonstrates the importance of local input in the acceptance of risk. The political leadership of Nevada is fighting the proposed repository and portraying their State as a victim, reinforcing the perception on the part of the broader public that the program is beyond local control.

The Department of Energy (DOE) should recognize that communications about the program will be ineffective so long as Nevadans believe they have no voice in the process. To the extent that DOE can share power, however, the increased perception of local control is likely to improve acceptance of a repository. The funding of a technical review group whose members are selected by the State government would be one positive step in this direction. In order to encourage rigorous technical analysis, it should be required that the findings of this review group include a statement of the technical evidence and reasoning behind the conclusions, as is done now by the State of New Mexico's Environmental Evaluation Group for the Waste Isolation Pilot Plant.

Given the highly polarized reactions to radioactive waste disposal, it is reasonable to anticipate criticisms and challenges to the technical competence and integrity of the program and its participants. Critics of the program point to the perceived incentives to find the proposed site and technology suitable, the motivation to meet schedules and budgets, and the resulting incentive to disregard or play down troubling findings. Claims to predict accurately events like earthquakes and climatic change are guaranteed to be challenged. These concerns have been addressed through a regulatory review process that is carefully designed to reveal errors, optimistic assumptions, and omissions; but the perceived credibility of that process can be bolstered if state and local groups and individuals have an opportunity to participate, not only in the formal review process but also through informal working relationships with project staff.

Those involved in HLW management must also avoid the trap of promising to reduce uncertainties to levels that are unattainable. Uncertainties are certain to persist. Whether the uncertainties in geologic disposal are too great to allow proceeding can only be judged in comparison to the projected risks and uncertainties for the alternatives, such as delayed implementation of disposal or surface storage of spent fuel. As a rule, the values determined from models should only be used for comparative purposes. Confidence in the disposal techniques must come from a combination of remoteness, engineering design, mathematical modeling, performance assessment, natural analogues, and the possibility of remedial action in the event of unforeseen events. There may be public desire or political pressure on implementing agencies to provide absolute guarantees, but a more realistic—and attainable—goal is to assure that the likelihood of unforeseen events is minimal, and that the consequences of such events are of limited magnitude.

Technical program managers may ask whether it is better for the public to know too much or not enough. When unforeseen events occur, for example, the public can raise questions about the validity of the technical approach, as well as the competence of the risk analysis that was used to justify it. Conversely, when foreseen events occur, they lead to questions about why they were not prevented. The technical credibility of the project team suffers in either case, but it probably suffers more when the organization has understated the risk or uncertainty.

Moral and Value Issues

Overview

The foregoing discussion suggests that, in the area of radioactive waste, ethical issues are as important as management and technical decisions. Interested parties approach the issues with different views about the right way to proceed, often due to differences in moral and value perspectives. As a result, an exploration of ethical issues can illuminate the fundamental policy debates in this field by showing the technical issues in their political and social context. Such an exploration also provides scientists with an opportunity to explore their own ethical responsibilities as they provide society with technical advice on controversial subjects. During its 1988 study session, the Board examined recent work on ethical questions in radioactive waste management conducted by scholars from a variety of disciplines.

These ethical concerns fall into two principal areas: (1) questions concerning the professional responsibility of scientists and engineers; and (2) questions concerning the appropriate uses of science in the decision-making process. Science and engineering are part of broader human activities, and as science enters the public arena, decisions can no longer be purely scientific; good science is not enough. Science has also become an important source of information and analysis for the public policy process, and scientists find themselves being called to account for, and to justify the results of, those decisions. Is this responsible, good, or desirable? How can the process be improved and the parties satisfied? Scientists have been sheltered from such questions in the past, but the increasing scale, sophistication, and pervasiveness of technical information require a corresponding increase in the sophistication with which these value judgments are made.

Three Issues of Equity

To see how questions of equity apply to radioactive waste management, consider first a study by Roger E. Kasperson and Samuel Ratick.[3] This project identified three sets of equity concerns, each of which raises questions of differential impact, public values, and moral accountability:

- *Labor.* Who does the work and who pays for it? Congress has determined that DOE will be responsible for the work and that the beneficiaries of nuclear power will pay for it through a surcharge on their electric rates.
- *Legacy.* What do we owe to future generations? Moral intuition tells us that our descendants deserve a world that we have tried to make better.[4] Posterity matters to us, independent of economic trade-offs; policy should therefore take that interest into account. The EPA regulation requiring evidence that radioactive waste releases will be limited for 10,000 years and more is an illustration of such a concern for the distant future.
- *Locus.* Who benefits, and who is exposed to risk? A repository is the final resting place for the waste from nuclear power plants that provide benefits spread over the whole nation for a short time; but it also concentrates risks and burdens along transportation routes and, for a much longer time, at the disposal site. A radioactive waste repository poses additional complications: it will be the first facility of its kind; the risks it poses are uncertain and, to the extent they exist at all, are likely to emerge over very long time spans; public fears are unusually high; and the history of federal action has raised

concerns about whether the interests of local populations will be treated equitably.

These ethical questions, when applied to radioactive waste management, demonstrate that once science enters the policymaking arena, good science is no longer enough, because technical decisions are no longer simply scientific. When the questions are no longer scientific, scientists alone cannot be expected to answer them. Sheldon Reaven suggests that the Nuclear Waste Policy Act (NWPA) creates a "scientific trap," in which citizens are encouraged to expect certainty from flawless science, and in which scientists and engineers are encouraged to believe or pretend that they can supply it.[5] Sheila Jasanoff makes the same point: the political need for accountability in the United States pressures regulators to seek a "scientifically correct" answer, even when there is none.[6] The attempt is doomed to scientific and political failure. It is therefore critical to recognize the boundaries of scientific understanding as it can be applied to a societal problem.

Five Issues of Policy

These ethical considerations have been applied to the current HLW situation by an interdisciplinary team led by E. William Colglazier.[7] For each of five key policy issues, the study discusses the "fairness" and appropriateness of the procedures for making decisions, the distribution of costs and benefits, and the type of evidence that is considered sufficient and admissible. The study places special emphasis on the role of scientific evidence because of the large scientific uncertainties and the continuing controversy, even among experts, on what is known and not known. The study's observations include the following:

• ***The need for the repository.*** The core policy dispute concerns the choice between permanent disposal in a geologic repository and long-term monitored storage in an engineered facility (including at-reactor storage) at or near the surface. The controversy has been over the distribution of costs and benefits to current and future generations and to various stakeholder groups:

—Pro-nuclear groups feel that the federal government promoted nuclear power and therefore has a special responsibility (spelled out in contractual obligations) to accept spent fuel in a timely manner for permanent disposal.

—Many environmental groups, on the other hand, view radioactive waste as a special threat to people and the environment; they also favor permanent disposal in order to fulfill this generation's responsibility, and view interim storage as an unfair "legacy" to future generations.

—Some proponents of interim storage, however, argue that this generation should not make decisions that would be costly to correct in the future; new technological developments may occur over the next century that could change our view of how to handle nuclear waste.

In short, all stakeholder groups agree that this generation should fulfill its responsibility to future generations, but they disagree on how to turn this value principle into policy.

• ***Siting.*** In making politically difficult siting decisions, political leaders have two basic options: make the choice internally and impose it on a weak constituency; or set up and follow a selection process perceived as objective, scientifically credible, and procedurally fair. When NWPA was passed in 1982, the latter course appeared necessary for both technical and political reasons. However, critics soon claimed that DOE was being political rather than objective in its decisions, citing as evidence DOE's choice of first-round sites and its decision to defer the second round of site selection. This perception led to a stalemate: DOE lacked credibility, and credibility is essential to implement the siting approach set forth in the NWPA. This stalemate was broken by Congress with the 1987 NWPA amendments, which designated Yucca Mountain, Nevada (one of DOE's first-round choices), as the initial site to be characterized and, if acceptable, to be licensed.

• ***Intergovernmental sharing of power.*** Procedural values were also important in NWPA, which established rules for sharing power among the affected governmental entities. However, the states feel that federal agencies, and especially DOE, have generally chosen to try to meet milestones rather than slow down the process to live up to the spirit of "consultation and cooperation." DOE, for its part, feels that it has a mandate to move forward expeditiously; it has tried to accommodate the states, which (in DOE's view) seek delays to throw obstacles in the way of efficient implementation. Nevada, in particular, interprets the 1987 NWPA amendments as unfair on procedural (as well as distributional and evidential) grounds.

• ***Safety.*** The fundamental safety issue is the determination of a fair evidential process and standard of proof for showing that the repository is acceptably safe for the thousands of years over which the waste will remain dangerously radioactive. The United States has adopted a set of licensing criteria (e.g., groundwater flow time, package lifetime, waste release limits, and so on) that require considerable certainty. As is often the case with frontier science, however, knowing more may actually increase rather than decrease the uncertainties, at least in the near term. The evidential uncertainties in assessing repository safety may point to a more flexible and evolutionary approach (see below); but this conflicts with the concerns to keep to a fixed schedule, so as to limit costs, discharge obligations to future generations, and meet contractual commitments to utilities holding spent fuel.

• ***Impacts.*** The debate over the distributional impacts of the repository program include such issues as who should pay for the program, how the impacts can be fairly calculated, and what is fair compensation for negative impacts. NWPA determined that the costs should be paid by the beneficiaries of nuclear-generated electricity through fees, initially, of one mill per kilowatt-hour. An evidential dispute concerns the potential "stigma effect," including lost jobs and lost tax revenues, due to nuclear waste; the social science methodologies for assessing this effect are still controversial. Another issue concerns the use of incentives and compensation: in the 1987 NWPA amendments, Congress authorized special payments for the host state, provided it forgoes its right to object. This runs the risk of being perceived by opponents as a bribe, offered in exchange for taking otherwise unacceptable risks. Congress also sought a procedural solution to these distributional impacts through creation of the Office of Special Negotiator, hoping that the negotiator might find an acceptable arrangement with the host state.

Consideration of these policy debates regarding the disposal of radioactive waste leads to three important conclusions:

- no interested party has an exclusive claim to be rational or to articulate the public interest;
- what is considered fair or unfair is subjective and can change over time;
- and with regard to repository safety, the issue is acceptability rather than certainty—acceptability being what is acceptable to society, given the evidential uncertainties, perceptions of risk, and contentious stakeholder debates.

These conclusions highlight the advantage of an empirical approach—one that examines fairness in process, outcomes, and evidence; one that reflects an understanding of the values as well as the interests of the stakeholders. Such an approach may lead to policies that have a greater chance of surviving over time because they are more widely perceived as fair.

Modeling and Its Validity

Overview

Models based on geological principles play a central role in the design and licensing of a waste repository. Because this is where science enters into the design and evaluation process, the Board discusses the appropriate use of models at some length, including the following topics: the purposes for which models are used; the relationship among modeling, treatment of uncertainties, and regulation; and supplements to the use of models in the current program.

The role of models in the design and licensing of the repository should properly be understood to be different from the use of models in designing airplanes or licensing nuclear reactors. There are major sources of uncertainty in quantitative geophysical modeling—even geohydrology, the best developed, can provide only approximate answers. Geoscientists will need more time to learn how to do more reliable predictive modeling of near-term events, and some events may prove to be chaotic—that is, impossible to predict in detail.

In particular, there is a critical need for (1) better communication between modelers and geological experts, in order to improve model prediction; and (2) a more open, quality-reinforcing process such as could be obtained through a peer-reviewed research program at universities and elsewhere. This would do much to improve technical and public confidence in models. DOE could support such an effort by allocating R&D funds, possibly through or in cooperation with the National Science Foundation, for model improvements.

In the meantime, however, models can be useful in identifying and evaluating significant contributors to risk and uncertainty. Models are not well suited to describe the risk and uncertainties to lay audiences, however. Natural analogues, if they can be found, are far more useful for this purpose (see below).

Problems of repository performance assessment, according to the scheme shown in Figure 1, belong in Region 2 or at the border between Regions 4 and 2. However, there is a general tendency to assume that we can address them using a Region 3 approach: that is, start with a deterministic model that incorporates all "relevant" contributors to overall behavior, and then attempt to collect enough data to move the problem from Region 2 into Region 3. In reality, however, this approach leads to increasingly complex models and increasingly expensive site evaluations, without a concomitant improvement in either understanding or design. Anthony M. Starfield and

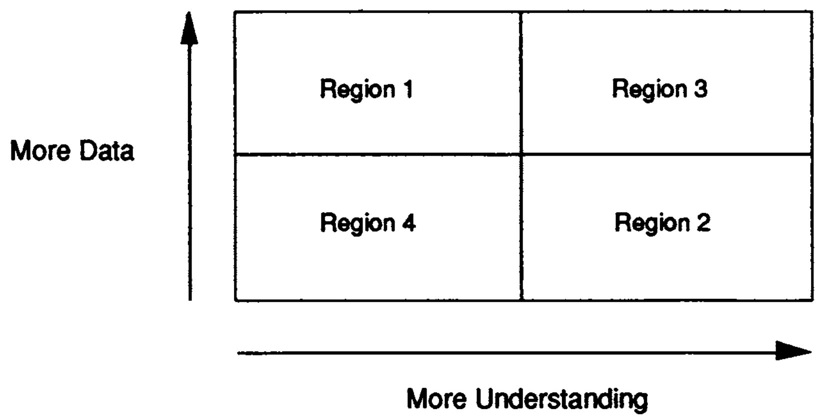

Figure 1. Types of modeling problems.

P. A. Cundall have suggested that we sometimes demand answers that the model is incapable of providing because of complexity or input demands. The design of the model should be driven by the questions that the model is supposed to answer, rather than by the details of the system that is being modeled. Under the present HLW program, geophysical models are being asked to provide answers to questions that they were not designed to tackle.[8]

Models and Modeling Problems

Figure 1 illustrates a general classification of the types of modeling problems taken from C. S. Holling.[9] In Region 1 there are good data but little understanding; this is where statistics is the appropriate analytic tool. In Region 3 there are both data and understanding; this is where models can be built, validated, and used with conviction. The use of finite-element models in structural design is a good example of Region 3 models. Regions 2 and 4 contain problems that are data-limited in the sense that the relevant data are unavailable or cannot be placed in a rigorous theoretical framework. In Region 2 the understanding of basic mechanisms is good; it is the detailed information that is unobtainable. In Region 4 there is not even a sound understanding of the basic mechanisms and interactions.

Appropriate Uses for Geophysical Models

In the Board's judgment, a scientifically sound objective of geophysical modeling is learning, over time, how to achieve the long-term isolation of radioactive waste. That is a profoundly different objective from predicting the detailed structure and behavior of a site before, or even after, it is probed in detail. Yet, in the face of public concerns about safety, it is the latter use to which models have been put. The Board believes that this is scientifically unsound. This conclusion is based on review of the modeling approach used by DOE and the regulatory agencies in order to implement the NWPA.

In order to support the regulatory and political argument that a site will be safe, it is necessary to make detailed, expensive, and extended extrapolations. These are informed speculations based on existing knowledge. In many instances the guesses are likely to be correct. The geotechnical models used to assure that the foundations of a building or bridge will be secure in the event of earthquakes provide an example of a well-founded predictive use of geophysical modeling. But to predict accurately the response of a complex mass of rock and groundwater as it reacts over thousands of years to the insertion of highly radioactive materials is not possible.

This point is important to the public concerns that have surrounded the U.S. radioactive waste program. Use of complex computer models is necessary to apply well-known geophysical principles in order to estimate or to set bounds on the behavior of a site, so that its likely suitability for a waste repository can be evaluated. But it is impossible to stretch the almost always incomplete understanding of a site into an accurate quantitative projection of whether a repository will be safe if constructed and operated there. Even after a detailed and costly examination of the site itself, only an informed judgment can be reached, and even then there will be uncertainties.

As modelers have become more aware of the processes they are attempting to model, they are also recognizing that the geological environment is more complex than originally thought and that quantitative prediction is correspondingly more difficult and uncertain. Many computer simulation models of geological environments are based on deterministic models that have been used successfully in branches of mechanics such as aerospace engineering, where the basic phenomena are much better defined. Such models are of limited value for the ill-defined, data-limited, long-term situations such as the repository isolation problem. It is illusory to expect accurate quantitative estimates of radionuclide releases from them.

Sources of Uncertainty in Geophysical Models

Performance assessments—estimates of the repository's ability to isolate HLW—are based on current computer simulations and parameters derived from laboratory and field measurements. As a consequence, they will have large uncertainties associated with the predicted performance. These uncertainties could pose serious obstacles in demonstrating compliance with licensing requirements. Discussions at BRWM's 1988 study session identified four principal causes of uncertainty:

1. ***Structural uncertainty.*** Do the equations adequately represent the operative physical processes? Do we in fact understand the system well enough to model it mathematically? Modeling will be most successful in solving Region 3 problems (see Figure 1), where we have a great deal of data and a good understanding of how the system works.

2. ***Parametric uncertainty.*** Have we chosen the right values for the variables (e.g., permeability) in the equations? Have we in fact chosen the right variables to represent the behavior of the system? Are our measurement techniques valid? Will they produce enough, and good enough, data?

3. ***Uncertainties in initial and boundary conditions.*** Have we interpolated adequately from a few spatially isolated point measurements to a broad three-dimensional domain (e.g., groundwater, heat, in situ stress)?

4. ***Uncertainties in forcing functions.*** How well can we characterize past and future events that might play a part in the fate of the repository (e.g., climate, tectonics, human intrusion)?

Urgent attention should be given to examining these and other causes of uncertainty, but even with continuing research along the present lines, improvement will come slowly. It may even turn out to be appropriate to delay permanent closure of a waste repository until adequate assurances concerning its long-term behavior can be obtained through geophysical studies. Judgments of whether enough is known to proceed with placement of waste in a repository are needed throughout the life of the project. But to repeat the Board's earlier point: these judgments should be based on a comparison of the available alternatives, rather than just a simplistic debate over whether, given current uncertainties, a repository site is "safe." Even when the detailed behavior of an underground repository is still under study, it may well be safer to put waste there, in a way that permits retrieval if necessary, rather than leaving it at reactors or in storage at, or near, the surface of the earth.

Modeling Limitations—An Example

The inherent difficulties of modeling are illustrated by the case of groundwater flow, which is used as an example precisely because it the best developed in terms of modeling. Groundwater flow has been extensively modeled for a broad range of engineering problems, and it consequently has a richer base from which to draw than do many other aspects of repository isolation. Groundwater flow is also generally accepted as the primary mechanism by which radionuclides could move from the repository to the biosphere, so it has been emphasized in modeling studies of repository isolation. Several experts, however, have commented on the difficulty of applying classical hydrology models to the problem of radioactive waste isolation.

> Groundwater hydrologists are becoming increasingly aware that inadequate and insufficient data limit the reliability of traditional deterministic [distributed-parameter] groundwater models. The data may be inadequate because aquifer heterogeneities occur on a scale smaller than can be defined on the basis of available data, time-dependent variables are monitored too infrequently, and measurement errors exist.[10]

> To carry out these [repository flow] calculations, hydrogeologists are applying geostatistical models and stochastic simulation methods originally developed to assess piezometric response in near-surface unconsolidated aquifers over limited spatial distances and short time frames with relatively abundant data. . . . These techniques may not be as valuable when applied to the assessment of radionuclide transport in deep rock formations, over large distances and long time frames, under conditions of sparse data availability. . . . [The authors] have repeatedly drawn attention to the potential problems associated with the geostatistical methods (Bayesian and otherwise) when data networks

are sparse and sample sizes small. In our opinion, this is the potential Achilles heel for the application of geostatistics at nuclear repository sites.[11]

With regard to repository isolation modeling, increased study has thus far resulted in the identification of greater complexity. Progress is being made toward including some of this complexity in the models, at least in terms of groundwater studies; but other geotechnical aspects of repository isolation (such as constitutive properties of rock joints, excavation and repository scale deformation behavior, and regional in situ stress) are far less developed. It will take years of additional research to represent them adequately in the models. As a result, the prospects are poor, especially in the short term, for models that can produce reliable quantitative measures of isolation performance.

Appropriate Objectives for Modeling

Repository performance assessments are unlikely to prove beyond doubt that risks are below established limits. Nor do the regulations require it—EPA requires only a "reasonable assurance." The problem is that in a case without clear precedents, it is unclear what is "reasonable." The Board's point is that unsound use of technical information is not a proper substitute for the political reasoning that, in a democratic society, must in the end win consent for taking reasonable steps to advance public health and safety.

In light of the limitations of technical knowledge, the Board concludes that it makes sense to conduct the assessments through an iterative process, in which the assessment provides direction to those characterizing a repository site and developing the repository engineering features. As further information is developed about the candidate site, it is also used in the performance assessment.

Many of the uncertainties associated with a candidate repository site will be technically interesting but irrelevant to overall repository performance. Conversely, the issues that are analytically tractable are not necessarily the most important. A key task for performance modeling is to separate the significant uncertainties and risks from the trivial. Similarly, when there are technical disputes over characteristics and processes that affect calculations of waste transport, sensitivity analysis with alternative models and parameters can indicate where further analysis is required and where enough is known to move on to other concerns.

Using Models to Reduce Uncertainty

Models do have an indispensable role in developing understanding of such problems, provided that the models are developed and used within the proper limitations. In other words, modeling can be used to improve models.

The following quotations from those concerned with such problems illustrate this point:

> . . . much time can be saved in the early stages of hypothesis formulation by the exploration of these hypotheses through mathematical models. Similarly, mathematical models can be used to investigate phenomena from the viewpoint of existing theories, by the integration of disparate theories into a single working hypothesis, for example. Such models may quickly reveal inadequacies in the current theory and indicate gaps where new theory is required.[12]

> The updating properties of the Bayesian approach . . . are well suited to the iterative approach we espouse for the modeling/data gathering sequence at a site. We feel that the first modeling efforts should precede or accompany initial site investigations.[13]

A good example of this general approach is the "regionalized sensitivity analysis" approach, by which G. M. Hornberger and his collaborators have been able to identify the "critical uncertainties" in applying a particular model to several data-sparse ecological problems and, thereby, to define programs of investigations to reduce those uncertainties.[14]

In summary, models should be qualitatively sensible, robust to sensitivity analysis, and independent of minor effects or processes, and they should include acceptable levels of uncertainty. However, models cannot prove that the repository is safe, nor can they resolve public concerns about the repository.

Supplements to Modeling

Natural Analogues. Because models cannot be conclusive with regard to the safety of a repository site, it is important to think carefully about natural analogues. These are natural "test cases," geological settings in which naturally occurring radioactive materials have been subjected to environmental forces for millions of years. These natural experiments demonstrate the action of transport processes that are similar to those that will govern the release of man-made radionuclides from a repository in a similar setting.

The natural analogue approach depends, of course, on whether the natural case is in fact an analogue for a repository situation. Where there is scientific agreement that the analogy applies, however, the approach is powerful because it allows us to predict processes with confidence over many millennia. And natural analogues can serve two additional roles: (1) they can provide a check on performance assessment methodology; and (2) they may be more meaningful than sophisticated numerical predictions to the lay public. The alternative management strategy described in the following section would make substantial use of natural analogues, such as undisturbed natural deposits of radioactive elements and groundwater systems, in order to illuminate the behavior of the geologic environment.

Professional Judgment. A second approach is to use the professional judgment of technical experts as an input to modeling in areas where there is uncertainty as to parameters, structures, or even future events. Such judgments, which may differ from those of DOE program managers and their staffs, should be incorporated early in the process. A model created by this process can redirect the DOE program substantially.

It is important to bear in mind that all uses of technical information entail judgments of what is important and what is less so. If the technical community is to learn from the successes and failures of the DOE program, it is essential that these technical judgments be documented. Setting out the reasoning of DOE staff and of independent outside experts contributes to learning and builds credibility in the process even when the experts disagree with DOE staff and among themselves.

Implications for Program Management

The Board has concluded that geological models, and indeed scientific knowledge generally, are being inappropriately applied in the U.S. radioactive waste repository program. That misapplication prompts this Board to outline an alternative management strategy. The next section describes an alternative management approach that employs natural analogues and professional judgment in a program design that uses science appropriately in the search for a safe disposal system. Putting such an approach into effect, however, would require major changes in the way Congress, the regulatory agencies, and DOE conduct their business. Such changes will be difficult to achieve, but the Board has reluctantly concluded that nothing else will put to rest the problems that plague the national program today.

Strategic Planning

Overview

There is no scientific reason to think that an acceptable HLW repository cannot be built and licensed. For historic and institutional reasons, however, DOE managers often feel compelled to "get it right the first time." This management strategy runs the risk of encountering "show-stopping" problems that may delay licensing and will certainly cause further deterioration of public and scientific trust.

The alternative would be a more flexible, experimental strategy that embodies the following principles:

- respond with conservative design changes as site attributes are discovered;
- use modeling to identify areas where more information is needed; and
- allow for remediation if things do not turn out as planned.

Implicit in this approach is the need to revise both technical design and regulatory criteria as more information is discovered. This is difficult to achieve in a governmental structure that disperses authority among legislative and executive agencies and separates regulation from implementation. When presented with intense controversy, such an institutional arrangement breeds distrust among governmental units and the public. In that setting, partial remedies further entangle the procedural morass.

More practically, however, DOE can enhance the credibility of the program and reduce the likelihood of late-stage surprises by (1) encouraging effective communication within its complex management structure; and (2) providing incentives for field personnel to identify and solve problems. DOE and the USNRC can also enhance credibility by encouraging periodic external reviews of the repository design, construction, and licensing requirements and associated processes.

Policy Context

The present U.S. approach to HLW disposal is increasingly vulnerable to being derailed by minor surprises. This vulnerability does not arise from a lack of talent or effort among the federal agencies and private contractors working on the program. Nor does the design or construction of the repository represent an unusually difficult technical undertaking. Instead, the program is at risk because it is following the wrong approach to implementation. The current predetermined process, in which every step is mandated in detail as in the more than 6,000-page "Site Characterization Plan,"[15] is inappropriate.

The current policy calls for a sequential process in which EPA and the USNRC first establish the criteria for safe disposal, and then DOE describes in detail what steps will be taken to move through site characterization, licensing, and operation of the facility. The result of this approach is that any late change, by any of the participating agencies, is taken as an admission of error.

And late changes are bound to happen. One worker was killed and five injured in an HLW repository under construction in West Germany when a support ring failed unexpectedly. At the Waste Isolation Pilot Plant (WIPP) in New Mexico, the discovery of pockets of pressurized brine in formations below the repository level led to public outcries and a continual National Research Council review of the suitability of the site.

The United States seems to be the only country that has taken the approach of writing detailed regulations before all of the data are in. Almost all other countries have established limitations on the allowable levels of radiation dose to individuals or populations resulting from repository establishment—but have taken a "wait and see" approach on design, while collecting data that may be of use in setting design. The United States, on the other hand, seems to have felt that detailed regulations can be, in fact must be, written without regard to any particular geological setting or other circumstance. As a direct consequence, the U.S. HLW program is bound by requirements that may be impossible to meet, even though overall dose limits can be achieved.

Alternative Management Strategies

The preceding sections have shown that there are a number of unresolved issues in the U.S. radioactive waste disposal program, as well as (and in part because of) high levels of uncertainty and public unease about the performance of the repository. The Board's consideration of these subjects indicates that the proper response to distrust is greater openness in the process, and that the proper response to uncertainty is greater knowledge and flexibility, as well as redundancy of barriers to nuclide transport. The U.S. program will continue to face controversy until it adopts a management strategy based on these principles.

The current approach to the design, construction, and licensing of the Nevada site is derived from the philosophy and procedures used for licensing nuclear power plants. The characteristics of the repository and its geological setting are carefully determined and specified as a basis for a complex set of calculations that describes the behavior of the system. This model is used to generate predictions of the migration of radioactive elements into the biosphere and analyzes the consequences of various events ("scenarios") that might affect the site over the next 10,000 years, in order to demonstrate that the repository site meets regulatory requirements (i.e., is "safe"). Based on the model and geologic studies of the site, the construction of the repository is specified in detail and then carried out under an aggressive quality assurance program, which is designed to withstand regulatory review and legal challenge. Within these requirements it is the geological setting that ensures isolation, not the engineered characteristics of the system; closure aims for complete entombment and discourages subsequent remediation. For all the reasons discussed above, a management process based on the regulation of nuclear power stations (a Region 3 type problem: see Figure 1) is inappropriate to the development of a waste repository.

A well-documented alternative to this approach is being followed, to various degrees, by countries such as Canada and Sweden. The exploration and construction of a geological test facility and a low-level waste repository, respectively, follow a flexible path, allowing each step in the characterization and design to draw on the information and understanding developed during the prior steps, and from prior experience with similar underground construction projects. During and subsequent to the closing of the repository, the emphasis will be on monitoring and on the ability to repair, in order to minimize the possibility that unplanned or unexpected events will compromise the integrity of the disposal system. Engineered modifications can be incorporated (e.g., in the waste containers or in the material used to backfill the repository) if the computer models suggest unacceptable or irreducible uncertainties in the performance of the unmodified containment system.

The Canadian experience at their Underground Research Laboratory provides a good example. All of the major rock structures and groundwater conditions were defined from surface and borehole observations before shaft construction began. Detailed geological structure can never be totally determined from surface information, however, and the final details of the facility design were modified to take account of information gathered during shaft construction.

What are the risks and benefits of the two approaches? The U.S. approach facilitates rigorous oversight and technical auditing. Its goals and standards are clear, and, if carried out according to specifications, this approach is robust in the face of administrative or legal challenge. It is designed to create a sense of confidence in the planning and operation of the repository, and it facilitates precise answers to specific technical questions.

However, such an approach is not consistent with normal geologic or mining practice. It assumes that the properties of the geologic medium can be determined and specified in advance to a degree analogous to that required for man-made components, such as reinforcing rods, structural concrete, or pipes. In reality, geologic exploration and mine construction never proceed in this way. Most underground construction projects are more qualitative, using a "design (and improve the design) as you go" principle. New sections of drill core often reveal surprises that must be incorporated into the geologists' concept of the site, integrated with past experience, and used to modify the exploration plan or mine design. In a project where adherence to predetermined specifications is paramount, the inherent variability of the geologic environment will result in endless changes in the specifications, with resultant delays, frustration for field personnel, high overhead costs, and loss of public confidence in both the suitability of the site and the competence of the professionals working on the project.

The second approach has more in common with research than with conventional engineering practice. This approach continually integrates new data into the expert judgments of geologists and engineers. It makes heavy use of natural analogues, such as undisturbed natural deposits of radioactive elements and groundwater systems, in order to illuminate the behavior of the geologic environment. It can immediately take advantage of favorable surprises and compensate for unfavorable ones. That this approach works well is evidenced by the enormous number of underground construction projects in diverse geologic settings that have been completed successfully around the world. These projects were not designed to contain radioactive waste for thousands of years, but many of them faced technical problems of comparable magnitude, such as crossing active faults, sealing out massive groundwater flows, or stabilizing highly fractured and structurally weak rock masses.

The second approach, with its reliance on continuous adaptation, would be much more difficult to document, audit, and defend before a licensing authority or court of law than is the more prescriptive approach. Some aspects of quality assurance can work well, such as document and sample control, the use of standard procedures and tools, and personnel qualifications. Other quality assurance techniques are likely to be contentious and may be impossible to implement in the same way they are implemented in nuclear power plants, including design control, instructions, procedures, drawings, inspections, and control of nonconforming items. An alternative is to use an aggressive and independent peer review system to appraise the decisions made and the competence of the technical personnel and managers responsible.

The legal system is able to accept expert opinion as a basis for action or assessments of action, but one cannot predict whether a repository could ever be licensed in the face of the batteries of opposing "experts" who would inevitably be called on to assess a flexibly designed and constructed repository for HLW disposal. The debate will hinge in part on a clear understanding of the alternatives against which a proposed "solution" will be judged. By contrast, the EPA standards and USNRC regulations define requirements that, if met, form the basis for the presumption that the facility is "safe."

Given the unhappy history of radioactive waste disposal in the United States, however, one very real and likely alternative is that nothing at all will be done. In judging disposal options, therefore, one should also adopt inaction or some other likely scenario as a default option, so that comparisons can be made and progress consistently assessed over time. The combination of a conservative engineering approach and designed-in maximum flexibility, to allow unanticipated problems to be corrected, should reassure both technical experts and concerned nonexperts. The barrier is not logical but institutional, and the prescriptive approach in the U.S. program is dictated by a governmental structure that separates regulation from implementation.

Within the present program, for example, "quality assurance" has become the bête noire of frustrated field personnel, who are trying to work within a system that is hostile to surprises in a world that is full of them. Because almost any geologic phenomenon has more than one possible cause, flexibility (including the recognition that uncertainty is inevitable and must be accommodated) is more likely to lead to the design and construction of a safe repository system than are rigid, predetermined protocols. In employing and evaluating such an adaptive approach to construction, emphasis focuses on those decisions that have irreversible or noncorrectable consequences on disposal, rather than on the myriad small adjustments that do not affect the basic flexibility and robustness of a repository.

The Elements of a More Flexible System

In a program governed by this alternative approach, change would not be seen as an admission of error; the system would be receptive and responsive to a continuing stream of information from site characterization. The main actors would reduce their reliance on detailed preplanning during initial site characterization, making it possible to debug the preliminary design during rather than before characterization.[16] But the necessary conditions of the system are flexibility and resiliency—flexibility to respond rapidly to ongoing findings in the geology, geohydrology, and geochemistry (within broad constraints); and resiliency to continuously adjust the performance assessment to reflect new information, especially where such information indicates possible precursors of substantial increases in risk. These qualities could be developed through the following steps:

- ***Iterative performance assessment.*** The basic approach outlined here would start with a simplified performance assessment, based on known data and methods of interpretation. Given the inherent uncertainties and technical difficulties of the process, the present system may well expend large efforts on small risks, and vice versa. An iterative approach, on the other hand, could allow characterization efforts to give priority to major uncertainties and risks, while there is still time and money left to do something about them. As in probabilistic risk assessment, analysis focuses on efforts to reduce the important risks and uncertainties. In this case, that means acquiring information on the design features and licensing criteria that are most likely to determine whether the site is suitable or should be abandoned.
- ***Fixing problems vs. anticipating problems.*** The underlying concept of the present, anticipatory U.S. management strategy is "Get it right the first time." One result is a 6,300-page "Site Characterization Plan" for Yucca Mountain. For the reasons described above, however, a process based on getting all of the needed measurements and analysis on the first pass, with acceptably high quality, is not likely to succeed. The geological environment will always produce surprises, like the pockets of pressurized brine at WIPP. No matter what technical approach is initially adopted, the design can be improved by matching it with specific features of the site. Experiments are now being conducted at WIPP with backfill material and other engineered barriers that were not part of the original design. These

are being tried as ways to make the disposal system as a whole robust in the face of newly discovered uncertainties in the geology.

• ***Define the problem broadly.*** As characterization proceeds, especially if it is done without the guidance of iterative performance assessment, DOE may eventually find it difficult or impossible to meet some of the criteria set by the USNRC and/or EPA. This will not mean that Yucca Mountain is unsuitable for a repository—the problem could be with the detailed criteria. This is no reason to arbitrarily abandon the release limits—it is the more detailed requirements that may need to be reconsidered, since they ultimately affect the release limits and the imputed dose. However, one should not take EPA's release standards or the USNRC's detailed licensing requirements as immutable constraints. They are roadmarkers to, and surrogates for, dose limits. Although the EPA standards and the USNRC regulations recognize and accept a certain level of uncertainty, the discussion to date of the application of these standards and regulations does not warrant confidence in the acceptance of uncertainty in licensing procedures.

Some process is needed in order to determine whether DOE's inability to meet a particular requirement is due to a disqualifying deficiency in the site or to an unreasonable regulatory demand, one that is unlikely to be met at any site and is unnecessary to protect public health. And to the extent that regulatory criteria can be corrected earlier instead of later in the process, they are more likely to be perceived as technical adjustments rather than as a diminution of public safety. Given the history of U.S. efforts to dispose of radioactive waste, current plans for the program have little chance of progressing without major modification in the 20 years or more that will be required to get a repository into operation.

RECOMMENDATIONS

The Board's conclusions are explicit or implicit throughout this document, as are many of the actions it would recommend to the various players. These recommendations are summarized below.

1. Congress should reconsider the rigid, inflexible schedule embodied in NWPA and the 1987 amendments. It may be appropriate to delay the licensing application, or even the scheduled opening of the repository, until more of the uncertainties can be resolved. The Secretary of Energy's recent announcement of a more realistic schedule, with the repository opening in 2010 rather than 2003, is a welcome step.

2. The Environmental Protection Agency, during its revision of the remanded 40 CFR Part 191, should reconsider the detailed performance standards to be met by the repository, to determine how they affect the level of health risks that will be considered acceptable. In addition, EPA should reexamine the use of quantitative probabilistic release criteria in the standard and examine what will constitute a reasonable level of assurance (i.e., by what combination of methods and strategies can DOE demonstrate that those standards will be met?).

All other countries use only a dose requirement. In setting regulatory standards and licensing requirements, the EPA should consider using only dose requirements.

3. The U.S. Nuclear Regulatory Commission, likewise, should reconsider the detailed licensing requirements for the repository. For example:

- What level of statistical or modeling evidence is really necessary, obtainable, or even feasible?
- To what extent is it necessary to prescribe engineering design, rather than allowing alternatives that accomplish the same goal?
- What can be done to accommodate design changes necessitated by surprises during construction?
- What new strategies (e.g., engineered features like copper containers) might be allowed or encouraged as events dictate?

4. The Department of Energy, for its part, should continue and also expand its current efforts to become a more responsive player in these regulatory issues. The following activities should be included:

- publicly negotiated prelicensing agreements with the USNRC on how to deal with the high levels of uncertainty arising from numerical predictions of repository performance;

- publicly negotiated prelicensing agreements with the USNRC on improved strategies for performance assessment;
- active negotiations with EPA and the USNRC on the real goals and precise definitions of their standards and requirements;
- an extramural grant program, in cooperation with the National Science Foundation, for the development of improved modeling methodology, in combination with training programs and public education efforts;
- expanded use of expert scientists from outside the program to review and critique detailed aspects and to provide additional professional judgment;
- greatly expanded risk communication efforts, aimed at reaching appropriate and achievable goals acceptable to the U.S. public;
- meaningful dialogue with state and local governments, Indian tribes, environmental public interest groups, and other interested organizations.

5. The Department of Energy should make greater use of conservative engineering design instead of using unproven engineering design based on scientific principles.
6. The Department of Energy should participate more actively in international studies and forums, such as those sponsored by the International Atomic Energy Agency, the Nuclear Energy Agency, and the Commission of European Communities, and should subject its plans and procedures to international scientific review, as Sweden, Switzerland, and the United Kingdom have already done.
7. Although geologic disposal has been the national policy for many years, and the Board believes it to be feasible, contingency planning for other sites and options (for example Subseabed Disposal of spent fuel and high-level radioactive waste) should be pursued. The nation, the Congress, the federal government, utilities, and the nuclear industry should recognize the importance of contingency planning in the event that some issue should make it impossible to license a geologic repository.

NOTES

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