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SUGGESTED TECHNICAL SCHEME TO HELP RESOLVE REGULATORY ISSUES

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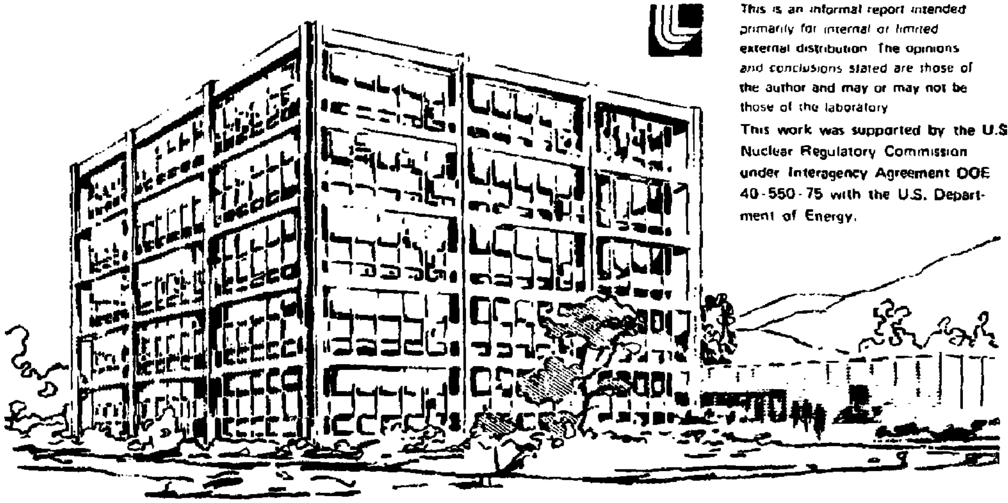

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FOREWOR

Decisions regarding nuclear waste disposal systems that are safe for thousands of years require the participation of systems analysts, geoscientists, and others. The different backgrounds of these participants and their different approaches to resolving issues lead to large gaps in the methodology for proving, a priori, that the waste disposal system is safe. Many meetings and conversations with members of different disposal disciplines have made it obvious that an explicit model is needed that can bridge the gap between a vigorous application of systems analysis and the other disciplines. The model would allow plans to be made for the ordered acquisition of data and for the development of performance prediction capability.

The present work describes the major features of one such model. If acceptable to the different disciplines involved, such a model would allow early detailed guidance to the U.S. Nuclear Regulatory Commission (NRC) and other agencies in the development of the national data base required to prove the safety of the disposal plan. The model itself, however, is not devoid of controversial issues. Ultimately, these issues must be resolved. Nonetheless, even in its current form, the model provides the framework for resolving many of the more important issues in the development of a technological data base. It has already proved useful in developing the data base used in many of the site suitability studies for the NRC.

The author would like to acknowledge the useful conversations with T. Holdsworth, Lawrence Livermore Laboratory, regarding several of the concepts presented in this work.

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ABSTRACT

A management-planning model envisioned as a useful tool for planning and guiding the development of a nuclear waste repository data base is described. It incorporates the technical assessment goals and objectives of the U.S. Nuclear Regulatory Commission, and it provides a strategy for reaching them. The model strategy includes provisions for the breadth, timeliness, and defensibility of its predictions. Consideration is given to observational data, its structure, and future refinements. The structure of the data is consistent with the needs of a systems model whose structure is proposed to resolve questions about repository safety.

Uncertainties are categorized as an aid in defining and resolving technical issues. The model provides a framework for ultimately exposing all the sensitive and controversial factors. Some quantitative aspects of data acquisition are presented.

INTRODUCTION

Evaluating the hazards associated with the disposal of high-level radioactive wastes in deep geologic strata demands that we acknowledge the uncertainties implicit in our predictions. These uncertainties by no means invalidate the findings of waste disposal studies, but only by properly accounting for the uncertainties can we assure that conclusions and forecasts will stand up to criticism. And only if the uncertainties are dealt with quantitatively is it likely that some disposal sites can be confidently evaluated as safe and that the sites with the greatest margins of safety can be identified. In addition, by identifying the sources of the uncertainties we can separate disposal sites that are merely unacceptable today (but that might become acceptable as technology improves and uncertainties diminish) from those that are clearly inappropriate for waste disposal. Identifying those same sources of uncertainty also provides direction for future research.

Prediction uncertainties in this scheme arise from three sources, which can be described as follows:

- Descriptive uncertainties. These include uncertainties in all the parameters used to describe the disposal site, for example, the dimensions of aquifers, the porosity of surrounding rock, the thickness of rock layers, and the temperature.
- Dynamic uncertainties. These are the uncertainties in the mathematical model used to predict the future dispersion of the waste. They include, for example, uncertainties in the dynamical laws that govern the interactions between the waste and the geologic environments.
- Random-event uncertainties. Events such as meteor strikes and earthquakes cannot be predicted, but they can be dealt with statistically. They form a third group of uncertainties.

If we were to take these sources of uncertainty to be independent, the total uncertainty in the predicted hazard from the buried waste could be written as

$$\sigma_{TOT} = \sqrt{\sigma_D^2 + \sigma_M^2 + \sigma_R^2} ,$$

where σ_D, σ_M, and σ_R are the uncertainties in the hazard due respectively to descriptive, dynamic, and random-event uncertainties. The total uncertainty is a reflection of the state of current technology--which determines how accurately we can describe the site and how accurately we can model future behavior--and is a measure of how confidently decisions and predictions can be made. Thus one of the obvious aims of residual uncertainty analysis is suggesting ways to reduce the size of σ_{TOT} by pointing to the sources of uncertainty most likely to yield to further work.

LLL WASTE MANAGEMENT PROJECT

GENERAL FEATURES

The LLL Waste Management Project uses the methods of systems analysis to look at the problem of nuclear waste management. We intend the project to evaluate the societal risk of burying waste in deep geologic strata and to establish a store of information that will serve as a data base for regulatory decisions.

The most important goals of the approach being taken can be summarized as follows:

- Breadth and flexibility. General types of sites, as well as specific sites, can be analyzed, and both predictable and random events can be accounted for.
- Scientific defensibility. A framework that exposes detailed technical issues can be obtained. Dialogue on these issues can then guide interested parties in developing the system and making forecasts.
- Timeliness. The project is organized as a series of cycles, each providing increasingly sophisticated results. These results are thus available at timely intervals during the project. A review of the results of each cycle also permits efforts to be redirected in the ensuing cycles.

FEATURES OF THE CYCLIC APPROACH

Each cycle of the waste management project is designed with the same general goals. The broad aims of each cycle of the site suitability subtask for example are:

- To quantify and reduce the uncertainties of hazard forecasts.
- To enlarge the available data base on which waste disposal decisions and environmental impact statements must be made.

However, approaching the waste management problem in a series of cycles allows us to adjust our specific approaches to these goals as each cycle begins.

Each cycle can then be seen as a continuation and refinement of the previous cycle--an iterative process.

Figure 1 shows how we might expect the resources available for each cycle to be divided. About half of the available resources are devoted directly to the aims of the project; the remaining half are spent in support activities, such as documentation. Of the former half, four-fifths carries on the effort of the previous cycle, one-fifth modifies and expands those efforts.

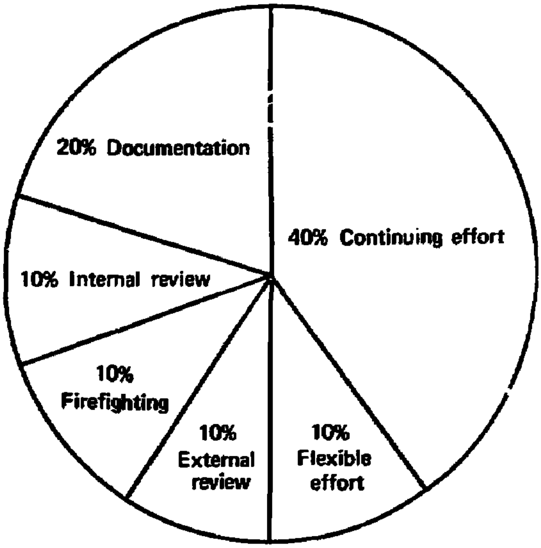


FIG. 1. A possible allocation of resources available during each cycle of the LLL Waste Management Project.

<u>Continuing Efforts</u>

The continuing efforts in each cycle of the site suitability subtask can be summarized as follows:

- Efforts to test and improve the dynamic model. This includes studies at the levels of both tier 1 and tier 2. (The three-tier approach is discussed below and is illustrated in Fig. 5.)

- Efforts to reduce the uncertainty of hazard forecasts by defining accurately descriptive and random-event uncertainties. This incl attempts to reduce the size of random-event uncertainties by lear enough about the random-event process that it can be incorporated the predictive model. As the project progresses it may also be possible to refine our treatment of controllable descriptive parameters. In studies of generic sites, the entire range of fea controllable parameters can be treated as a descriptive uncertain analyses become more site specific, the values of controllable parameters can be established more precisely. More will be said b about controllable parameters.
- Efforts to identify the parameters with the greatest impact on estimates of radiological hazard.
- Efforts to improve ways of displaying results. The results of ear cycles were often presented in tabular form; efforts are now being to include quantitative graphical presentations along the lines of of the figures in this report (especially Figs. 2, 3, and 12).

Flexible Efforts

Flexible efforts are those that distinguish one cycle from those that pre it. They represent an allocation of resources along those lines that ea studies have indicated to be most promising. They include:

- Efforts to extend earlier studies to new geological media that hav been proposed as repository sites.
- Efforts to study physical processes and events that have not yet considered. These will first be studied in tier 1 models, then i warranted, incorporated into the dynamic model.
- Efforts to revise priorities so that the most important descriptiv parameters receive the most attention.
- Efforts to study the feasibility of objective analysis of the data Fig. 7).

HAZARD ASSESSMENT

To fully assess the hazard of buried waste over a broad range of some descriptive parameter, say aquifer length, three pieces of information ar necessary:

- A best estimate (or preferred value) of the hazard as a function of aquifer length over the range of plausible aquifer lengths.
- A range of uncertainty around the preferred value that accounts for descriptive, dynamic, and random-event uncertainties.
- An accepted radiological performance objective (RPO), a goal that defines the upper limit for release of radioactivity from a geologic repository.

Figure 2 illustrates how this information might be displayed. In this case, based on the RPO shown, aquifer lengths to the right of the vertical dashed line could be assumed safe with high confidence.

We can also use Fig. 2 to make two other points. First, it is clear that the range of uncertainty must be carefully established to ensure that regulatory decisions can be made with confidence. If the uncertainties were left vague,

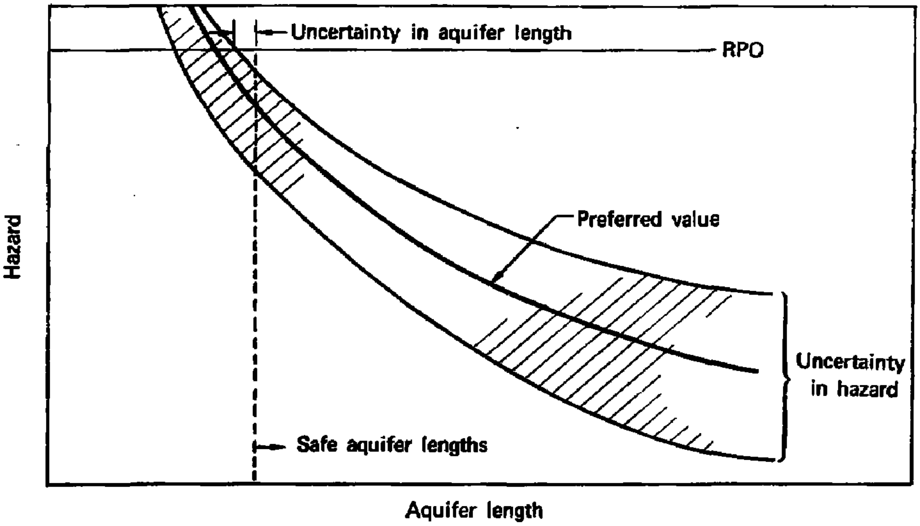


FIG. 2. Estimate of radiological hazard as a function of aquifer length. Aquifer lengths to the right of the dashed line ensure radiological hazards below the RPO. The range of uncertainty can reflect any level of confidence desired.

conclusions based simply on the preferred value would not be scientifically defensible. Second, the figure illustrates the heavy dependence of regulatory decisions on the RPO, a subject that will be mentioned again later in this section. Let it suffice here to say that in the current example the only reason the hazard must be evaluated precisely beyond the dashed line is the uncertainty about where the RPO will be established.

ALLOCATING EFFORT

One of the most important benefits of quantifying the uncertainties of hazard estimates is an increasing ability to judge which sources of uncertainty might be easiest to reduce. We can then direct our efforts to those areas most likely to yield results. Often the uncertainties in the extent of the hazard are dominated by uncertainties in the parameters used to describe the disposal site. Such cases point to more thorough exploration or improved measurement technology as keys to greater confidence in hazard predictions. In other instances, where the site itself can be described with more confidence, the hazard uncertainties may be largely due to random-event uncertainties or to uncertainties in the dynamic model. If our analysis reveals that the total uncertainty is dominated by uncertainties in the predictive model, we can again effectively direct our efforts to improving the confidence of our predictions. Many random-event uncertainties, on the other hand, cannot be effectively reduced by improved technology or by further analysis, so they provide a limit to our confidence. In a later section, we will discuss our approach to random-event uncertainties. In any case, they appear infrequently to be the most significant contribution to the total uncertainty.

In addition to distinguishing among sources of uncertainty, we can draw a distinction between controllable and uncontrollable descriptive parameters--and again it is a distinction that helps determine where our analytical energies might best be spent. Uncontrollable descriptive parameters are those beyond technological control. An example is the permeability of the rock, once a site has been chosen. Controllable parameters, for example, the dimensions of the depository rooms, are those over which we have some control. Figure 3 is an example of one way we might use this distinction. The radiological hazard (including its range of uncertainty) is plotted as a

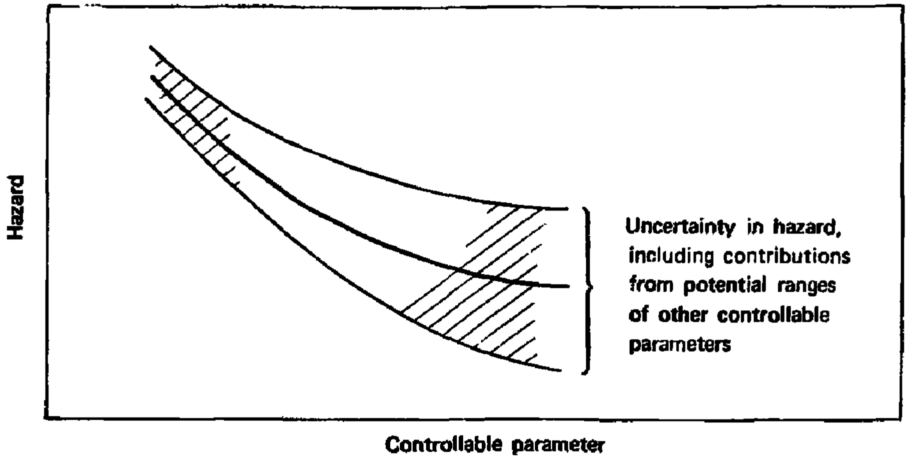


FIG. 3. Estimated radiological hazard as a function of a single controllable parameter. The breadth of the crosshatched area includes contributions from all uncontrollable parameters and from the potential ranges of all but the single controllable parameter plotted on the abscissa.

function of a single controllable parameter, say, depth of burial. This plot then becomes a guide to how deep the waste must be buried (in this hypothetical instance) to reduce the hazard below a certain level. Notice that the potential ranges in all the remaining controllable parameters contribute to the total range in the hazard. Careful analysis of controllable and uncontrollable parameters will indicate which sites proper technology might make safe and which are beyond its control.

SOCIAL UNCERTAINTIES

We have already alluded to the uncertainty in the RPO--an uncertainty in some respects not amenable to analysis, since it depends on social and political judgments and on philosophical values. In any case, it is beyond the scope of this work to evaluate or predict the RPO. Our estimates of radiological hazard and our analysis of descriptive, dynamic, and random-event uncertainties are made without assuming a given performance objective.

Another uncertainty beyond the scope of the current study is any nontechnical, political constraint on siting decisions. For example, for any number of political reasons, the technically safest waste disposal scheme might not be available. Two examples of current political and policy constraints are (1) international treaties that prohibit seabed disposal of waste, and (2) nonproliferation policies that prohibit waste reprocessing. If these constraints were removed, a safer disposal scheme might evolve.

Though we will not consider social and political uncertainties again in this report, it is useful to illustrate how they might vary with time, and how siting decisions might depend on them (Fig. 4).

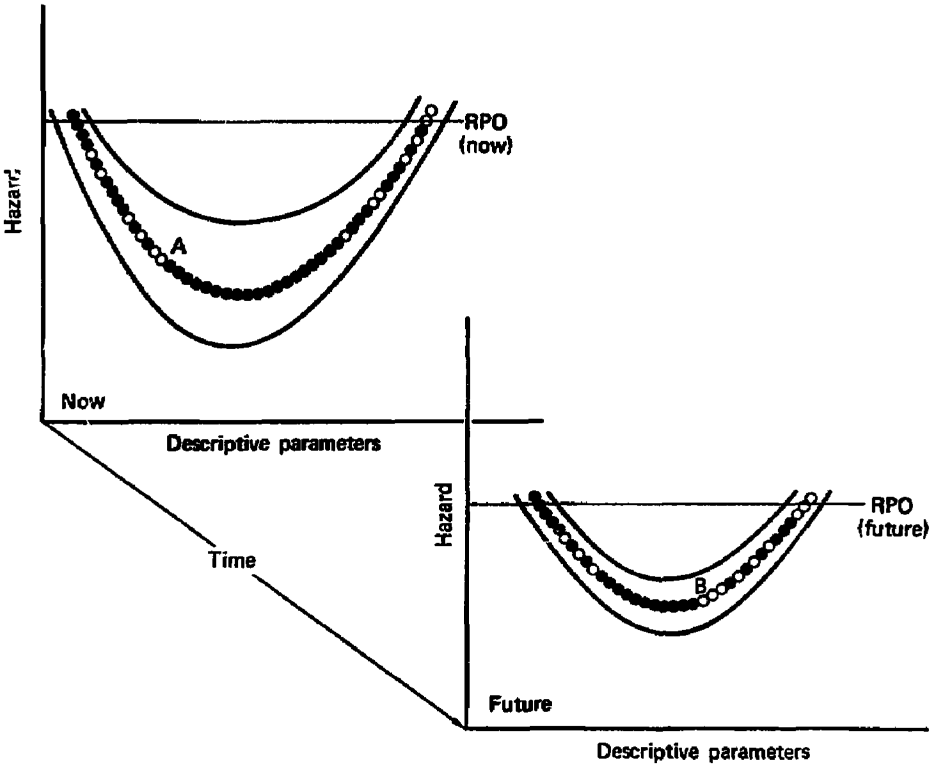


FIG. 4. Schematic representation of the time-dependent behavior of political parameters. In this example, the radiological performance objective becomes more restrictive as time passes, but the uncertainty in the estimate of the hazard diminishes, as do the number of politically unacceptable sites. The politically unacceptable sites are designated by closed circles, those acceptable as repository sites by open circles. The safest site available today would be at A (where the maximum credible hazard is lowest), whereas in the future it would be B.

TECHNICAL APPROACHES TO THE PROBLEM

MODEL DESIGN

The mathematical systems-analysis model that predicts the future behavior of buried waste must yield accurate, technically defensible results--as well as quantify the uncertainties--yet be simple enough to be computationally tractable. We have sought to achieve both of these goals by proposing the three-tier approach illustrated schematically in Fig. 5. The central feature of the scheme is the predictive model itself (tier 2), which is based initially on the approximations and insights afforded by the rough models of tier 1. At first, then, the predictive model can be thought of as being well to the left in Fig. 5, where its defensibility is low. As the program progresses, tier 3 provides state-of-the-art models to test the assumptions in the predictive model and to supply rigorous numerical input. Therefore, benefiting from feedback from both tiers 1 and 3, the model migrates to the right, toward greater scientific defensibility.

In addition to the general design of the computational scheme (Fig. 5), a second means of improving model efficiency is to provide, whenever possible, input data in the form of scaling sets. For example, where a single flow path is the dominant barrier to the biosphere, the travel time across the flow path for a radioactive pulse is given by

$$t_e = \frac{z^2 \phi K_f}{kp} ,$$

where

z = length of flow path
ϕ = effective porosity
K_f = retardation factor
k = hydraulic conductivity
p = driving pressure.

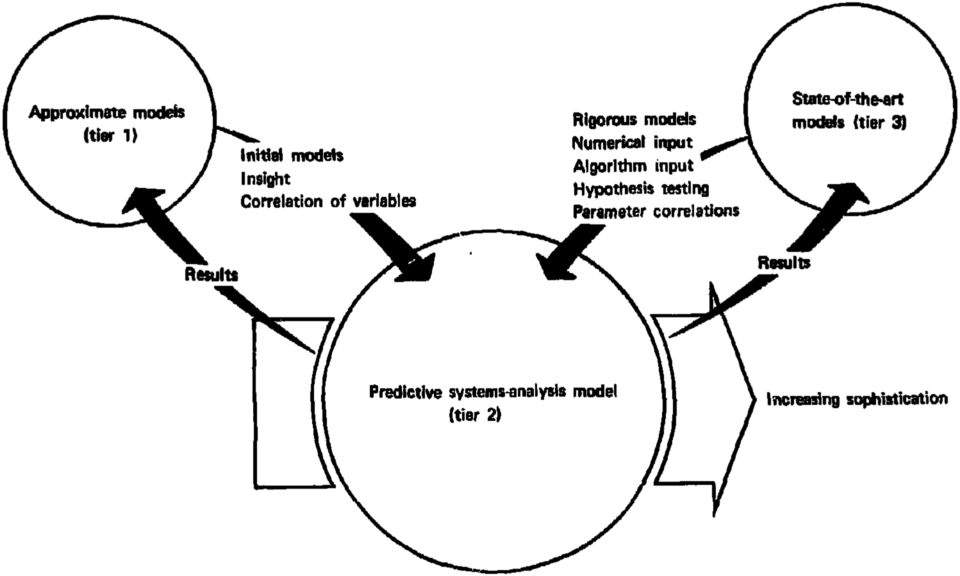


FIG. 5. Schematic illustration of the systems-analysis model used to predict the future behavior of buried waste. The model becomes more defensible as it benefits from both approximate models (which provide initial insights) and state-of-the-art models (which provide tests of assumptions and approximations). This three-tier approach ensures that the model is both accurate and computationally efficient.

Therefore, assuming that longitudinal dispersion can be accounted for separately, an analysis need only consider a range of values for t_e (rather than z, ϕ, K_f, k, and p separately). These five descriptive parameters, interrelated as shown, constitute a scaling set. These scaling sets not only reduce the amount of computer time required for an analysis (by simplifying the input), but also provide insight into the tradeoffs among descriptive parameters.

HANDLING DESCRIPTIVE DATA

Generic and Specific Sites

It is possible to assess not only specific sites that have been proposed as waste repositories, but also more broadly defined generic sites. An analysis of a specific site uses whatever descriptive parameters are available for that site, and the accuracy of the analysis depends in large part on how precisely these parameters have been defined by exploration. Analysis of generic sites provides much more general information. In these latter cases, the uncertainties in the descriptive parameters must encompass all possible values for the type of site being analyzed. For example, if we are making an analysis of a generic site in layered rock, we must consider all plausible values for the porosity of layered rock.

Distribution of Parameter Values

The statistical distribution shown in Fig. 6 has been chosen to describe the uncertainties in descriptive parameters. This description (derived from a lognormal distribution) is defined by

$$P(V,V_{min},V_{max},U) = \frac{N(V_{min},V_{max})}{V\sqrt{2\pi}\,\ln U} \exp\left\{-\frac{1}{2}\left[\frac{\ln (V/V_{1/2})}{\ln U}\right]^2\right\},$$

where

U = geometric standard deviation of parent lognormal distribution

V = value of descriptive parameter

V_{min} = minimum plausible value of V

V_{max} = maximum plausible value of V

$V_{1/2}$ = median value of V of parent lognormal distribution

$N(V_{min}, V_{max})$ = normalization factor.

The distribution is normalized so that

$$\int_{V_{min}}^{V_{max}} PdV = 1.$$

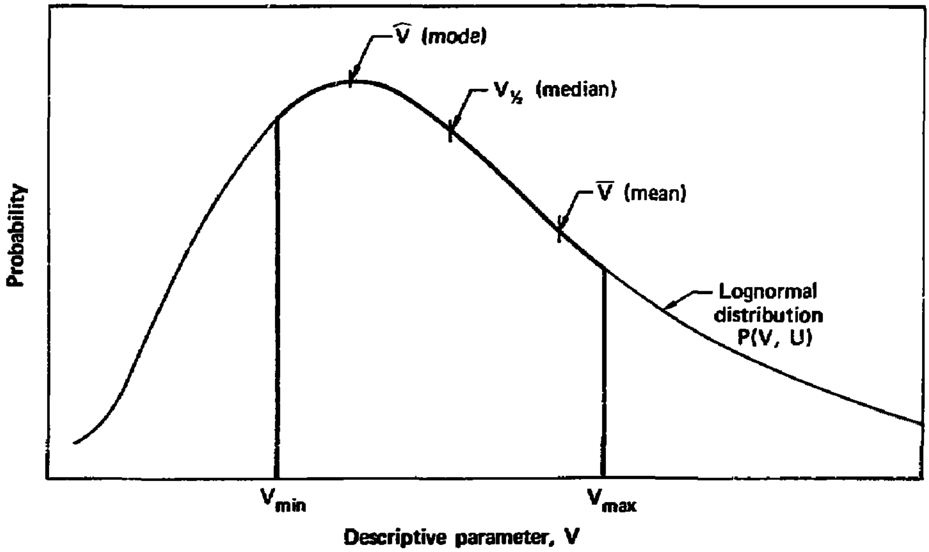


FIG. 6. The distribution used to describe the range of values for descriptive parameters.

This distribution is especially convenient when uncertainties range over several orders of magnitude, and it can be justified physically. The physical justification assumes that unless descriptive parameters are very accurately specified ($U << V_{max}/V_{min}$), one well-behaved distribution is as good as another, as long as it spans an adequately large range of parameter values (see Fig. 7a). When the descriptive data is very precise, we can either continue to use the skewed distribution described in Fig. 6, and assume that other uncertainties will overwhelm any errors introduced by its skewness, or if necessary we can substitute a more symmetrical distribution (see Fig. 7b). The relative values of the variables that describe the distribution determine its general shape and can be used to arbitrarily define three increasingly sophisticated levels of analysis. Figure 8 illustrates typical shapes and lists the characteristics of each of these levels.

The first level depends only on expert opinion (based on available data) for the median parameter value ($V_{1/2}$), the credible range of parameter values (bounded by V_{min} and V_{max}), and the value of the parameter (U) that specifies the breadth of the parent distribution. At this stage of analysis, the range must encompass all plausible values for a generic site, and the value of U is chosen very large. The result is a flat, featureless distribution function covering the range of possible parameter values.

The second level of analysis corresponds to a phase of exploration and data gathering. It depends on better data for each generic site and is characterized by a more confident estimate of $V_{1/2}$, a smaller value for U, and a smaller range of plausible parameter values. At this level the distribution function for a given parameter still cannot be regarded as rigorously quantitative, since the analysis depends not only on an incomplete data base, but also in part on expert judgment.

The third stage culminates the evolution from informal analytic methods to a formal inductive technique. It requires a substantial body of carefully analyzed data, which can be put in an appropriate mathematical form. A physical model for the parameter must then be developed using regression analysis. This level of analysis demands a thorough understanding of exploratory techniques and uncertainties, of relevant physical processes, and

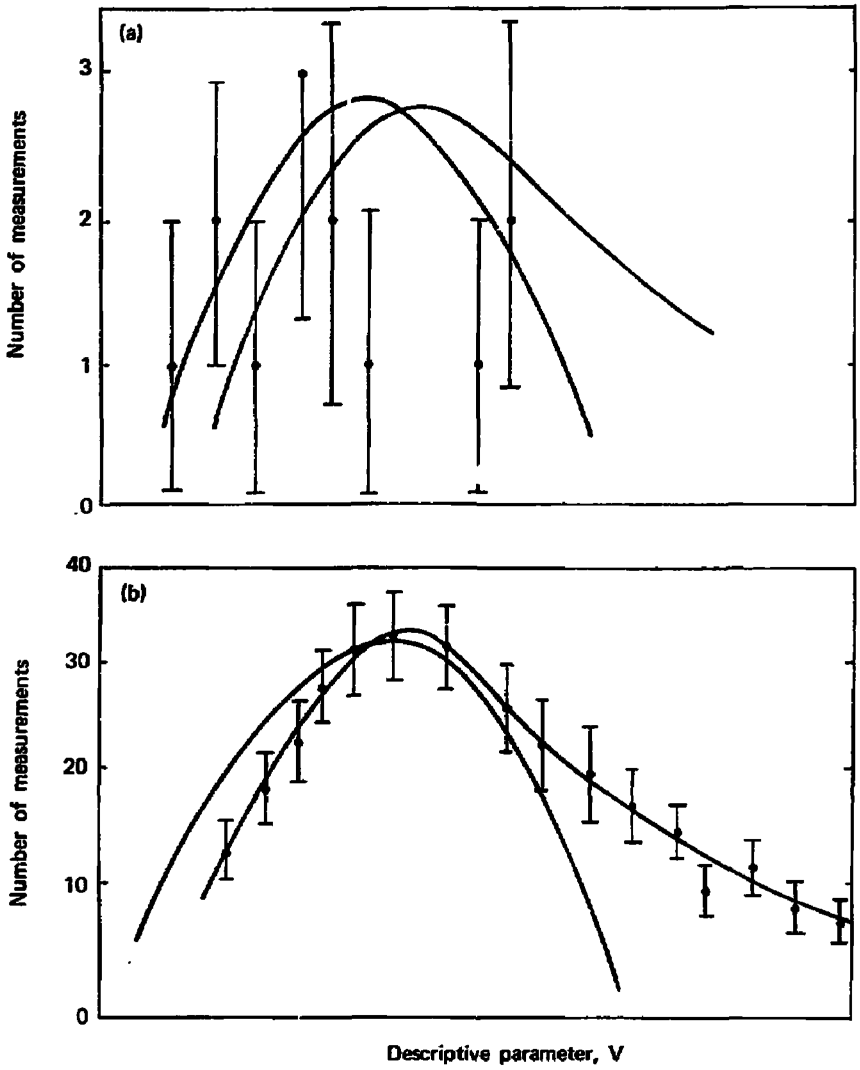
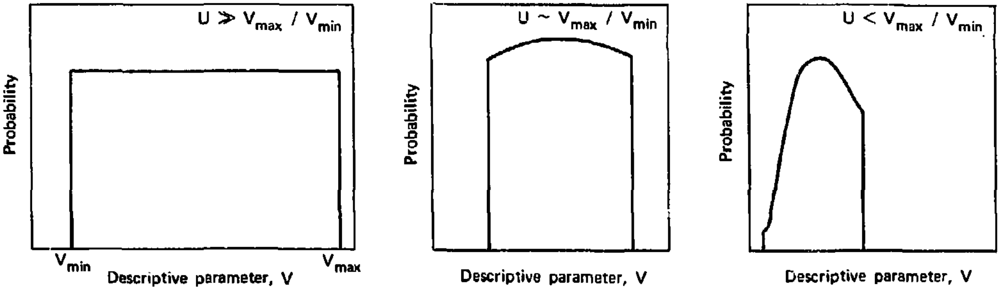


FIG. 7. Effect of data-base size on the statistical distribution. In (a), where few measurements have been made and the data are scattered, either of the distributions shown will suffice, provided it adequately covers the entire range of plausible parameter values. In (b) the data are precise enough to distinguish between alternative distributions.



Expert opinion

- Guesses based on available data
- Encompasses plausible range of values
- Applicable to generic sites

Subjective analysis

- Parallels effort to gather further data
- More realistic range of values
- Applicable to narrower range of generic sites
- Probability distribution not quantified

Objective analysis

- Demands numerical analysis of data
- Applicable to specific sites or narrow range of generic sites
- Quantified probability distribution

FIG. 8. Three levels of analytical effort. Each can be described by the relative values of the variables used to define the probability distribution and by several general characteristics. The uncertainty in the hazard prediction decreases as the descriptive information improves.

of laboratory analytical methods. The result is a still more confident estimate of the descriptive parameter. Since this final stage demands considerable resources, it is practical only for some descriptive parameters--where more accurate analysis is likely to improve substantially the confidence of hazard forecasts.

Parameter Correlations

When establishing the uncertainties of descriptive parameters, it is important to recognize that some parameters may be closely correlated, for example, the permeability and the porosity of rock. If this correlation were ignored when making forecasts for generic sites (where parameter uncertainties are considerable), we would unduly emphasize the unrealistic situations where permeability is high and effective porosity low. The high permeability would lead to the calculation of a relatively high radionuclide flux, and the low porosity would demand that this flux be translated into a very high radionuclide velocity. The result would be an unrealistically high estimate of the potential hazard.

Figure 9 illustrates schematically how pairs of parameters might be

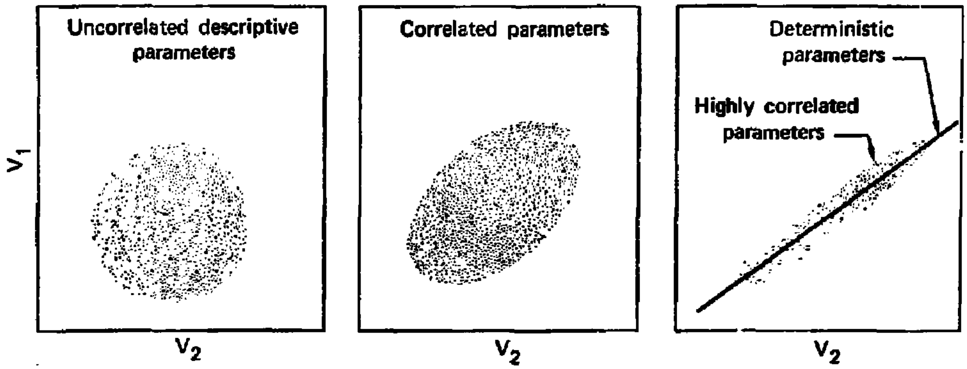


FIG. 9. Range of correlations between descriptive parameters. At the left, descriptive parameters V_1 and V_2 are uncorrelated; the illustrations to the right show an increasingly strong relationship between the two parameters.

correlated. Where sufficient data are available, quantitative distribut (Fig. 6) are useful for quantifying such correlations.

Interpolation As A Source of Data

In some cases data may not be available for a descriptive parameter for a being analyzed. However, if a tested physical model exists that relates needed parameter to known parameters, the data can be inferred, rather th directly measured. In many cases, this amounts to interpolating between experimental results relating parameters using a numerical formulation lik that shown in Fig. 10. Such interpolations carry with them rigorous statistical distributions. In this example the data fit a curve describe

$$V(W) = \frac{a}{W^b} .$$

The uncertainties in the constants a and b can be calculated by nonlinear regression analysis, and a new parameter value, $V(\tilde{W})$, evaluated as

$$V(\tilde{W}) = \frac{a \pm \Delta a}{\tilde{W}^{b \pm \Delta b}} .$$

Once models like the one in Fig. 10 have been developed and inferences mad we can accurately judge whether additional measurements should be made to assure greater confidence in inferred values. For example, in Fig. 10, an experimental measurement of V at W' would greatly decrease the uncertainty inferences in the vicinity of $\tilde{W}$.

HANDLING STOCHASTIC PARAMETERS

In addition to uncertainties in the dynamic models and in the descriptive parameters, we must account for uncertainties due to events we cannot mode deterministically. Among stochastic events that must be considered in any long-term risk analysis are breccia pipe formation, backfill failure, clima changes, meteor strikes, earthquakes, and social changes.

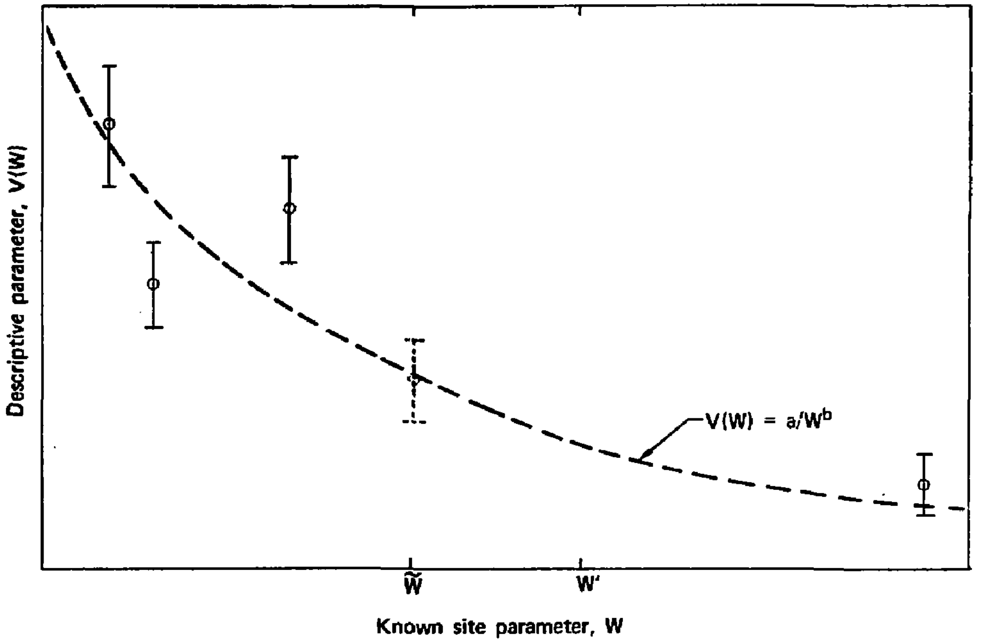


FIG. 10. Derivation of descriptive parameters by inference. If a physical model can be reduced to a numerical formulation on the basis of known data, further parameter values can be inferred by interpolation. This curve also suggests that a measurement of V at W' would significantly improve our confidence in inferences of $V(\tilde{W})$.

We might also include such catastrophic events as solar novae and nuclear warhead strikes, but in comparison with the direct consequences of such disasters, any release of radioactivity from repositories is unimportant.

Converting Stochastic to Deterministic Parameters

Some events that superficially appear to be unpredictable random events can, in principle, be understood as deterministic processes. An example is the formation of breccia pipes. This geophysical process, though not currently a predictable phenomenon, can probably be understood in terms of geometry, hydrology, geochemistry, and thermal history of the waste disposal site. Ultimately, therefore, breccia pipe formation is likely to be removed from the list of stochastic parameters and made part of the dynamic predictive model, and its uncertainties will become dynamic, rather than random-event uncertainties.

It is important to incorporate such processes as breccia pipe formation into the dynamic model (or among the descriptive parameters), since dynamic and descriptive uncertainties are easier to evaluate than random-event uncertainties, and since several such processes play important roles in the prediction of radiological hazards. Climatic change is another process, now thought of as largely random, that might ultimately be understood in terms of descriptive parameters and dynamic models.

Other events, such as earthquakes and meteor strikes, are likely to remain analyzable only as stochastic events. Although the analysis of these processes has a direct effect on the hazard forecasts, the best estimates of hazards will usually be only slightly affected by truly random events. Likewise, we expect random-event uncertainties usually to be obscured by much larger dynamic and descriptive uncertainties. Only when random events, such as earthquakes, appear to be the major sources of hazard (or uncertainty) will we attempt to analyze them in detail.

Time-Dependent Catastrophic Events

Some catastrophes, such as meteor strikes, occur unpredictably with a constant probability that is not time dependent; however, the probability of other nondeterministic events, especially those associated with social and political activity, varies with time. Figure 11 illustrates several examples, based on the following three assumptions:

- The probability of canister or backfill failure is initially zero, but increases to a large value over a period of many thousands of years.

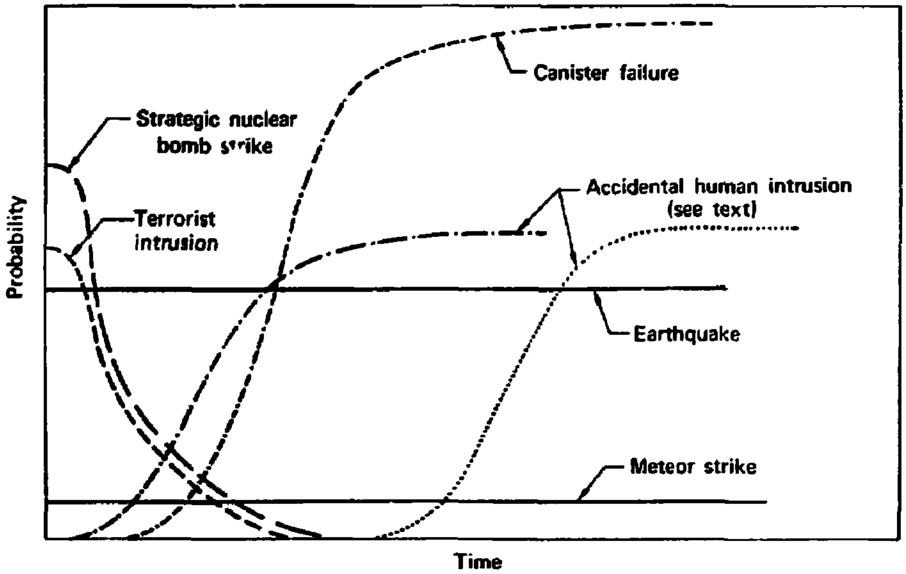


FIG. 11. Probabilities of several time-dependent catastrophic events compared with constant probabilities of meteor strike and earthquake. The assumptions that underlie the time-dependent curves are discussed in the text, as are the factors that influence the curves for accidental human intrusion.

- The political climate improves so that the prospect of a nuclear bomb strike and the prospect of terrorist intrusion decrease to near zero in about 100 years.
- Administrative policing of the site initially ensures against accidental human intrusion, but the risk of intrusion increases with time. The time at which risk becomes appreciable depends largely on the public perception of the need to continue policing the site and on government stability. (This variability is illustrated by displaying two curves for accidental human intrusion in Fig. 11.)

We can gain further insight into the consequences of these time-dependent events by evaluating the hazard in several specific scenarios. In Fig. 12 the five curves represent the hazards that would result from accidental human intrusion at the five times indicated on the abscissa. Plots such as this clearly indicate the time during which the integrity of the site must be maintained.

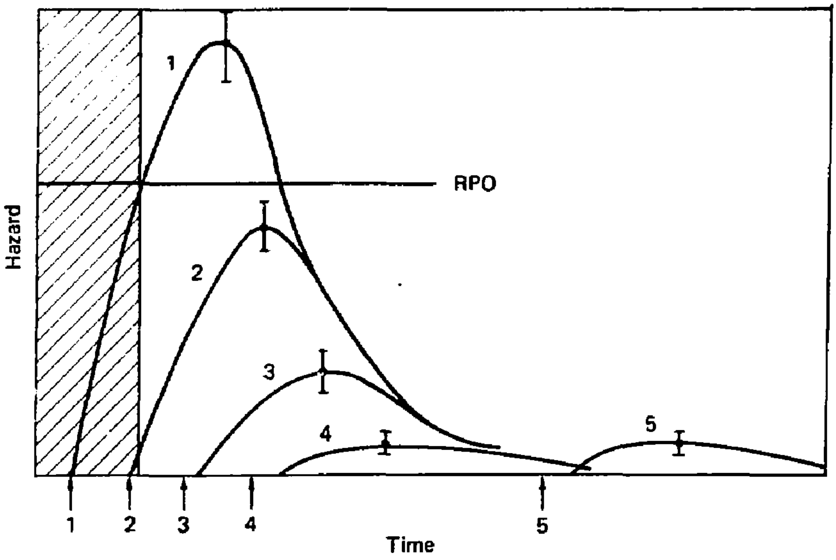


FIG. 12. Consequences of human intrusion for five different scenarios. The five curves illustrate the hazard that would result from accidental human intrusion at the five times indicated on the arbitrary time axis. The error bars represent the uncertainties in each hazard estimate. To avoid risk of a hazard that exceeds the established safety standard, integrity of the site must be ensured during the time indicated by the crosshatched area.

CONCLUSION

Today's technology is good enough to bridge the gap between detailed repository physical factors and the impact on society of the performance of these physical factors operating as a nuclear waste disposal system. This includes the ability to incorporate the uncertainties that exist in today's data base. Many techniques exist to handle these uncertainties, and different experts favor different techniques. However, if carefully used, most techniques will lead to similar conclusions. Therefore, our main thrust, in expediting waste management, should be to choose a methodology that is sufficiently general to provide the needed results and to submit it to the concerned community as soon as possible.

It was in this spirit that the conceptual models in this report were established. At the least, they provide a structure that can be used to reduce many of the modeling gaps that exist. Other choices could be made; our concern is that the worst choice is to make no choice at all.

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