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A FRAMEWORK FOR TREATING UNCERTAINTY TO FACILITATE WASTE DISPOSAL DECISION MAKING - APPLICATION OF THE APPROACH TO GCD PERFORMANCE ASSESSMENT

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ABSTRACT

This paper presents an approach for treating uncertainty in the performance assessment process to efficiently address regulatory performance objectives for radioactive waste disposal and discusses the application of the approach at the Greater Confinement Disposal site. In this approach, the performance assessment methodology uses probabilistic risk assessment concepts to guide effective decisions about site characterization activities and provides a path toward reasonable assurance regarding regulatory compliance decisions. Although the approach is particularly amenable to requirements that are probabilistic in nature, the approach is also applicable to deterministic standards such as the dose-based and concentration-based requirements.

I. INTRODUCTION

In this paper, we focus on an approach for treating uncertainty in the performance assessment process to confidently address regulatory requirements for radioactive waste disposal. In this approach, the performance assessment methodology uses probabilistic risk assessment to guide effective decisions about site characterization activities and provides the necessary reasonable assurance regarding regulatory compliance decisions.

For geologic waste disposal, we are typically interested in the performance of a system for hundreds or thousands of years and over large spatial scales of meters to kilometers. In general, we are uncertain about what might actually occur at our site in the future, how these events will manifest themselves, and what the magnitude of their impact will be. We are uncertain because we cannot know everything there is to know about the system, nor can we predict with complete certainty what the system will look like in the future. This uncertainty notwithstanding, we are still required to make decisions about disposal site safety and decisions about how to manage resources to ensure safety with some level of confidence.

In general, we describe "treatment of uncertainty" as the process by which we analyze our state of knowledge about a given system for a given purpose, describe that state of knowledge and uncertainty in a way that is useful for decision making, and then decide where it is of value to gather information to increase our knowledge and reduce our uncertainty. The purpose of this process is to make a specific decision about which action to pursue given a set of alternatives with a certain objective in mind. In performance assessment, this is systematically handled through the identification of sources of uncertainty, description and quantification of the uncertainty, propagation of the uncertainty through the execution of process models, and reduction of uncertainty where and when necessary. The goal of this process is not to perfectly understand the real system, but to understand it well enough to make a confident decision. In waste disposal performance assessment, our decisions are generally of two types: (1) can a site be licensed or certified as acceptable for its intended purpose and (2) what information should be collected or what actions should be taken to support the decision under (1). We propose the following process for enabling efficient and defensible answers to these questions.

II. FRAMEWORK FOR MANAGING UNCERTAINTYAND DECISION MAKING

The framework for managing uncertainty and facilitating decision making is shown as a generalized flowchart in Figure 1. Initially, the site's performance is evaluated based only on existing and available data and information. This information provides the foundation for representing the current state of knowledge, or conversely, state of uncertainty. Therefore, uncertainty would be greatest at this initial step and should only decrease as the process proceeds (e.g., models assumptions refuted, parameter

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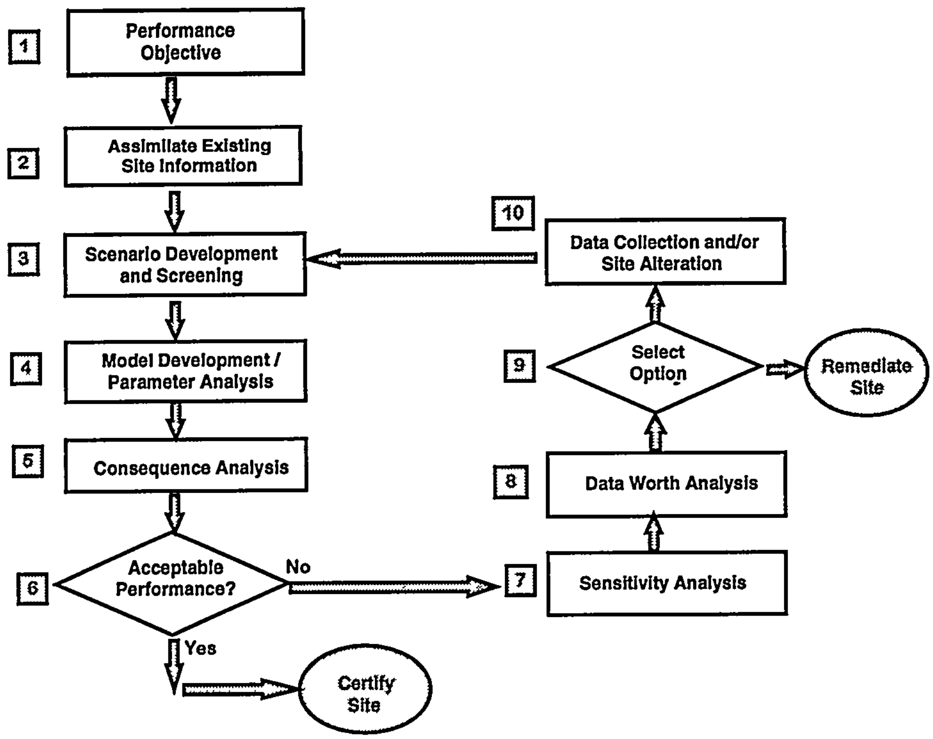

Figure 1 - Framework for managing uncertainty and decision making

distributions narrowed). If acceptable performance (i.e., compliance) can be defensibly demonstrated based on this initial set of information, then there is no need to proceed further, and the site can be certified. If acceptable performance cannot be demonstrated with this initial set of information and analyses, then the optimal strategy for the site is identified by looking at options for alternative actions, including uncertainty reduction through data collection, and proceeding with the best alternative. The framework provides a logical, integrated approach for assessing and demonstrating compliance, providing documentation, and involving concerned parties. Following is a description of each of the framework components and how they integrate to define a process for progressing through the framework to treat uncertainty and define a compliance strategy.

To begin the process, the performance measures (e.g., cumulative release, dose), performance objectives (a threshold value that defines compliance), and decision criteria (acceptable percent of results that must be less than the performance objective or acceptable level of confidence in results) need to be defined (Step 1). Then, existing information on the site is gathered and assimilated in the context of Step 1 to understand the general nature of disposed source and the physical systems and processes that the site represents (Step 2). A key point of this framework is that any *new* site data collection does not take place until Step 10. New data collection is deferred until the data that would make a difference in decision making and are cost effective to collect can be defined through sensitivity analysis and data-worth activities. Otherwise, money may be spent on collection of superfluous data. Next, the analyst must determine all the significant and reasonably foreseeable events and processes that affect the system (i.e., scenarios) over the regulatory time period, including progression of the system under its current conditions (Step 3). These generally include natural and human induced stresses on the system. Models are developed to describe and quantify, under uncertainty, the system's response to these stresses (Step 4) and provide the needed information to compare to the performance objectives, allowing a technical foundation for decision making. Generally, qualitative and descriptive conceptual models are developed, and then translated into mathematical models and implemented in (and solved by) corresponding analytical or numerical models and computer codes. This quantitative analysis is referred to as consequence analysis (Step 5) and provides the foundation for evaluating the viability of the facility/system. The objective of these analyses is to qualitatively compare the modeled system's response to the regulatory performance objectives and to assess whether the site complies with those requirements (Step 6) with some level of confidence. If it can be defensibly demonstrated that the site complies with the regulatory performance objectives, the site operator or other responsible party would then proceed to submitting a certification of license application, upon whose approval, the site would be accepted for disposal. If under Step 6, it cannot be demonstrated with confidence that the regulatory performance objectives can be met, then alternative actions for demonstrating compliance with an acceptable level of certainty (Steps 7 and 8) would be identified and evaluated. These options may include the collection of additional information to reduce uncertainty in the current analysis and hence defend lower calculated releases, remediation of the site, redesign of the site, or any combination of these. Potential data collection activities are identified through sensitivity analyses (Step 7) and their relative worth is evaluated against alternative actions (Step 8). Based on this analysis, the preferred option is selected (Step 9) and carried out (Step 10 or Remediate). Based on the resulting modification to the site or the new information about the site, the analysis is refined accordingly and the site is reassessed. If the data collected support compliance, then effectively, the technical analysis is complete.

The framework is designed such that the level of complexity and rigor of analysis conducted for a given site should be commensurate with the level of risk that the site poses. Implicitly, this would include both the level of uncertainty at a particular site and the magnitude of the expected health risks that the site poses. Both of these are critical components in determining how robust a site is. In other words, the level of effort that it would take to step through the framework for a simple site where few processes exist to transport contamination should be much less than that required for a complex site where many possible processes exist. In this context, simple and complex refer to the level of uncertainty about the compliance decision and not the level of uncertainty about how the real system operates.

A. Risk-Based Approach to Decision Making

The approach that we advocate in this framework integrates risk into the decision making process by evaluating:[1]

- what can happen (e.g., radionuclides move through soil to ground water to a person)
- what is the likelihood/probability of occurrence (e.g., what is the uncertainty in the processes that lead to contaminant migration and exposure)
- what are the resulting consequences (e.g., cancer)

Each of these is a critical consideration in that we must explicitly evaluate our uncertainty to make effective decisions. The decision making process or decision analysis takes this information and integrates into a logical process for deciding what is the best alternative action that should be taken to maximize the likelihood of meeting our end objective.

A decision represents the commitment of resources that is revocable only at some cost.[2] We make decisions based on the value of a given performance measure as compared to a specified performance objective that we are trying to meet. These "values" in our case could be the quantified system performance in terms of contaminant release, cost of alternative actions, combinations of these, or some other measure.

Decisions are generally made based on both existing knowledge and the possible outcomes of future events for which we do not have perfect knowledge or information about. That is, for a waste disposal system for example, we understand certain constraints about the specific system and in many cases can define boundaries for behavior; however, we do not know and will never know everything about critical processes in time and space. Nevertheless, we are still required to make decisions in absence of this perfect knowledge. Consequently, we look at the possible outcomes following a decision, and the likelihood of those outcomes, and we make our decision based on this. To do this requires an expression of the uncertainty in such a way that we can evaluate when the uncertainty does make a difference in our decision, and when it does not make a difference in our decision. Furthermore, if the uncertainty does make a difference in our decision, we need to express it in a way that will allow us to identify and reduce the critical uncertainties to maximize the probability of a good decision. As a consequence, decision making is not defensible within a deterministic framework, unless the deterministic quantities have been determined through explicit consideration of uncertainty.

In this particular waste disposal decision problem, we are trying to attain specified performance objectives. Specifically, the analysis is attempting to define and select alternative actions that would minimize releases from the site and also minimize the cost and time needed to implement the necessary actions. In addition, for the technical regulatory performance objectives, we have defined threshold values below which there is no value in reducing uncertainty.

B. Types and Sources of Uncertainty

Because we are dealing with the performance of a natural system over hundreds or thousands of years and over several kilometers, we expect to have much uncertainty about how the system will behave and respond to specific disturbances. At the highest level, the uncertainties that must be dealt with include the nature and magnitude of the physical behavior of the site now and in the future, and the nature and impact of future human activities at the site. It is important to recognize that although these uncertainties about how the "real" system will evolve may be great, they are only of consequence in this process if they make a difference in the decision regarding compliance. At another level, we have uncertainty in the efficacy of particular actions that could be taken to either collect additional information about the system or to control certain aspects of the system. For example, we may have several alternatives for site data collection or facility design/alteration; however, we do not know with complete certainty *a priori* what the outcome of these actions will be.

As a matter of convenience for this discussion and to facilitate management of uncertainty, we have separated the types of uncertainty associated with assessing the system's performance into three general categories:[3,4] (1) uncertainty in the likelihood of occurrence of future events (2) uncertainty in the models that describe those events, and (3) uncertainty in the parameter values that quantify the description and output of the models.

1. Uncertainty in the Likelihood of Occurrence of Future Events

Although there will be only one progression of events and processes, we do not know what exactly that progression will be. Therefore, plausible future states of the disposal system (often called scenarios) are considered in a performance assessment. These scenarios can represent possible natural evolution of a site, future land use by humans, or a combination of these. Uncertainty in the future state of the system is typically handled one of the following ways:

- specification of the future state of the system as one of many combinations of a suite of possible future events and evaluation of the system's response to each of these future states;
- specification of a finite set of future human activities and behaviors at the site (often defined by regulatory guidance) and evaluation of the site under each of these sets of conditions; and,
- evaluation of the site's evolution through models of large-scale stresses on the system over time (e.g., long-term, large-scale climate modeling).

In practice, these are usually combined in some way. Scenarios are not predictions of the future, but rather provide a tool for managing the uncertainty at a high level by defining a limited number of discrete possible future states. Therefore, they should be developed such that they can guide decision making. Depending on the risk preference of the decision maker, the scenarios may attempt to bound future evolution of the site, they may attempt to provide a representation of the most likely conditions at the site in the future, or they may attempt to do both. Of course, there is no way to guarantee that a set of scenarios bound future conditions at the site or that they accurately represent future conditions at the site.

Under certain regulations, the scenarios are assigned probabilities of occurrence and the results combined into a single set of output upon which the final compliance decision is based. For example, this is the approach taken under EPA's regulation for disposal of high-level waste, transuranic waste, and spent fuel.[5] Under other regulatory approaches, pre-defined scenarios are treated independently and separately, are not assigned a probability of occurrence, and the conditional outcome from each and all scenarios is used as the basis for decision making. That is, the results from each scenario would not be weighted by a probability and the outcome from all scenarios would have to meet the performance criteria for the site to be in compliance. This is the approach typically taken for low-level waste disposal in the United States.

When dealing with uncertainty in the occurrence of a random future event, there really is no such thing as a correct probability. That is, probability is used to represent an individual's or group's degree of belief that something will or will not occur. When dealing with the frequency of an event that occurs once or many times over some specified period of time, then there exists a statistical likelihood (i.e., frequency) for that event over some specified time period. Given enough trials, a "correct" statistical frequency could be reasonably well defined and known (e.g., coin flip). For natural events (e.g., earthquakes, floods), we often use the term "probability" to describe the statistical likelihood or frequency that the event will occur over some time period, and its value is generally founded in natural historical evidence or technically-based theory. For example, estimates of the probability of an earthquake that will send Los Angeles sliding into the ocean are generally based on the frequency of past tectonic activity in that area and technical understanding and theory of how that fault system will continue to evolve into the future. There could of course, be uncertainty in the value of the frequency estimate because of a lack of perfect information about a given system. Human-induced or human-controlled events (e.g., changes in the stock market, well drilling for mineral exploration) are fundamentally different from geologic processes, and in these cases we often discuss "probability" as a combination of statistical frequency and trends based on past behavior, and uncertainty in future behavior (humans are odd creatures that are difficult to predict).

In the approach described here, we can accommodate both these definitions of probability. If there are conflicting values for the probability of a disruptive event, we would begin the process with the highest value for the probability. For example, two experts may be given the same information about the system and based on alternative interpretations of that information, provide alternative values for the probability of say, meteorite impact at the site. If under the higher value of probability, the scenario proves to be of no concern, then there is no further need to reconcile the differences in the probability estimates. In this case, there would be no value in collecting additional data or spending energy to resolve the conflicting opinions. If on the other hand, the two probability estimates lead to different decisions about how to proceed, then there is likely value in collecting information to reconcile the differences. In the second case, the additional data collection would be directed at reducing uncertainty such that a more informed decision could be made. This would only work if the difference in opinion is due to a data uncertainty or ambiguity, or modeling limitation (i.e., it is possible that there are no activities that would resolve the conflicting opinions).

In the case where scenarios are treated separately and are not assigned probabilities, under the decision approach in this paper resources would be directed toward refuting specific scenarios or exposure pathways of concern within scenarios. This is possible in the case where the initial set of scenarios are defined generically and are thought to be conservative, and where site specific information would lead to a less conservative representation of the scenario.

2. Uncertainty in Conceptual and Analytical Models That Describe Events and Processes

Models are developed to simulate and describe the possible responses of the disposal system to certain stresses brought on by the occurrence of the events discussed above. A model is a simplification of the existing and future system. In making this simplification, assumptions can be justified as long as:

- the assumption is reasonable in that it is close to actual conditions and can be defended as such with site-specific information
- the assumption is conservative in that a more realistic representation based on site-specific conditions would not yield higher output (e.g., dose).

The output of these models is the "value" around which the decision maker will make their decision regarding compliance with the technical criteria. Models are necessary because (1) direct testing of the system response over the time and space scales of interest to give us the information we need is neither practical nor possible, and (2) we still need to make decisions in light of the absence of this information. For our purposes, the conceptual model describes how the contaminants move from the source to the accessible environment. The mathematical models, and the numerical links between those models, are the equations that implement the conceptual model. Treatment of model uncertainty includes the development and analysis of alternative conceptual models, the propagation of the uncertainty through the consequence analysis using mathematical and numerical models, and the reduction of uncertainty through focused data collection.

When dealing with geologic systems where we do not know all spatial characteristics, and because we cannot perfectly know the future over any time frame, a realistic conceptual model is not attainable. Consequently, uncertainty in the conceptual model is expected to exist. In other words, more than one possible interpretation of the system can be justified based on the existing information. We propose that this uncertainty should be addressed by developing multiple alternative models of the system and proceeding forward through the framework with all the conceptual models that are consistent with available data (i.e., models that are not refutable) and also result in releases that exceed the performance criteria. The reasons why the models that result in noncompliance are of most interest are: (1) any one of the suite of models that is consistent with the data is equally likely to be representative of the site and so the decision to accept the site should be made based on the models that result in failure to comply; (2) if compliance can be demonstrated with all plausible models, then confidence in the decision to accept the site is achieved; and, (3) as we step through the process, it is much more likely that we can define activities that refute certain assumptions versus activities that will unequivocally support certain assumptions. Note that the conceptual models that result in unacceptable releases will be determined through quantitative consequence analyses (Section 2.3).

This process for model development and modification forces the analyst to develop models that focus on resource allocation and regulatory decision making. That is, the results of the analysis based on these models are by no means a prediction of how the system will respond. Rather, they provide the basis for simulations of plausible outcomes for this system given a particular level of knowledge, provide information for and focus on situations that would be a cause for concern, and therefore provide a foundation for decision making. Any models that result in acceptable performance are of less concern and therefore, energy and resources should be directed toward resolving those models that cause problems; therefore, this facilitates resource allocation decision making. Because we would like to minimize the probability of making an incorrect decision (accepting a poor site or ruling out a good site), we are more concerned with possible ways to refute the models that result in noncompliance. Consequently, this process for treatment of model uncertainty facilitates regulatory decision making.

3. Uncertainty in Parameter Values

In this step, the analyst defines the model parameter values and quantifies the uncertainty and variability in each of the parameter values. Assignment of quantitative parameter values is necessary because it provides the mechanism for quantifying the information that comes out of the models.

Treatment of parameter uncertainty includes the development of quantitative descriptions of possible parameter values, the propagation of uncertainty by exercising the models with a variety of possible parameter values, and the reduction of uncertainty through focused data collection. Quantification of parameter uncertainty is generally handled by developing quantitative parameter distributions that act as a representation of the distribution of possible values that could be realized for a given parameter and provide information about the likelihood that particular values will exist versus other values. Typically, these parameter distributions incorporate information on both uncertainty and variability in the parameter value. The development of parameter distributions is closely related to model uncertainty in that the parameter distribution in and of itself represents an assumption about the system, and because the parameter values used to define the distribution are almost always derived through interpretation of data measurements using modeling assumptions.

Parameter uncertainty is a function of the amount and variability in data used to support the parameter values, the uncertainty in the interpretation of those data, as well as uncertainty in the data values themselves. For example, there may be several equally defensible methods for converting spatially and temporally variable data into effective model parameters, and each of those methods may produce a different effective value. In other words, parameter uncertainty is a description of the level of knowledge about a given parameter's values and it is typically represented by a probability distribution. In general, the probability distribution provides a quantitative description of the possible range in parameter values given our state of knowledge and the likelihood of experiencing specific parameter values. For example, if we assigned a uniform distribution to a parameter with a range of zero to ten, we would be saying that, given our state of knowledge, the parameter could be any value between zero and ten, and furthermore, it is equally likely to fall in any of the intervals between zero and ten. Other types of distributions would imply that the parameter value is more likely to fall in some intervals than others, but it could fall anywhere in the range of the distribution.

Parameter variability, on the other hand, is a description of the diversity of actual values that occur for a parameter that is heterogeneous, and is typically described by a frequency distribution. For example, if we had enough money, we could sample body weights of all individuals in the United States and develop a distribution of those body weights. This distribution would describe the variety or range of body weight across the U.S. and the distribution of people across specified intervals. In this case we would have very little uncertainty in this distribution because (1) we have sampled all individuals in the population, and (2) there was almost no interpretation required to go from the data values to the parameter of concern (i.e., with a good scale, body weight could be measured almost directly). If we only sampled a subset of the population, or if we used a model to infer weight from samples of height for example, then we would have some uncertainty in our description of the variability.

In modeling, we often develop and use effective values of parameters that represent the equivalent parameter value over some spatial or temporal scale. For example, we may model our system using an effective value of hydraulic conductivity over the total scale of interest although we know that at smaller scales, a variety of values of hydraulic conductivity will likely exist. We do this because (1) for our purposes there may be no value in resolving the parameter at the smaller scales, or (2) it may not be possible or practical to measure the parameter at all scales and an approximation is required. If a single effective value represents the parameter value in our model, then given enough information, we could define what that single effective value is. Consequently, the distribution that represents this parameter incorporates only uncertainty in the parameter value and not variability. It is important to note that the definition and distribution of the effective value should be consistent with the overall approach in that if data were collected to resolve the parameter values at all scales, the resulting effective value derived from these small scale values would not fall outside of the original distribution for the effective value.

In summary, there can be uncertainty in what a single value for a parameter is for a given member of the population or at a given point in time and space, as well as, uncertainty in the variability of a given parameter over space, time, and population.

In this approach, we advocate that parameter uncertainty be presented as a representative, unbiased distribution that reflects our current state of knowledge for a given parameter. For fixed value parameters (i.e., one value exists, but we do not know exactly what that value is), this implies that the parameter distribution covers the entire possible range over which that parameter might exist. For variable parameters (i.e., many values exist, but we do not know exactly what the description of the variability is), this implies that the parameter distribution should cover the entire range over which the actual distribution could possibly exist.

Definition of the parameter distributions in this way is required to conduct meaningful sensitivity and data worth analyses. This is because in the sensitivity and data worth analyses, we are evaluating where reduction of uncertainty in the output is possible and where reducing uncertainty in input parameters is of value. In the extreme, if deterministic, biased values for particular parameters are used, then there is no meaningful basis for a sensitivity analyses using these parameters; consequently, the value of certain data collection activities (data worth) ends up being predisposed toward those parameters where unbiased distributions were initially specified.

C. Propagation of Uncertainty

Propagation of uncertainty involves the agglomeration of the different sources of uncertainty after they have been quantified and the implementation of the system models to produce an output distribution of values of our performance measures. This output distribution represents the range of possible outcomes that are plausible given the models of the system, and given our current state of knowledge.

Propagation of model and parameter uncertainty in the performance assessment analyses is relatively straightforward. For this approach, Monte Carlo simulation is advocated to propagate parameter uncertainty through models to results of analyses. To derive the output distribution for the performance measure using Monte Carlo sampling, we initially draw a random sample from each of the input parameter value distributions. For example, if we had a parameter that ranged from zero to ten, we may draw a value of 6.4. We do this for all the parameters to provide an input data set to run the mathematical/numerical models of the system. Once these models are run with this single set of input values, we produce one possible value of the model output. This procedure is repeated multiple times (100's or 1000's), each time producing one possible value of the performance measure. This process results in multiple possible values of the performance measure, from which we can define our output distribution. As a result of the random sampling procedure, each value of the performance measure that is produced by the model is as likely as any other value.

More comprehensive discussions for propagating uncertainty in data and parameters have been presented elsewhere.[6,7,8,9,10] The Latin Hypercube Sampling (LHS) technique[11] has been proposed to obtain samples for the Monte Carlo simulations because using LHS reduces both the number of samples that are needed to span and represent the range of uncertainty in parameters and the number of samples that are needed to honor correlations between parameters.

To propagate and address uncertainty in conceptual models, we should evaluate each of the models that leads us to have concern. Often, we do not know if a model causes concern (i.e., results in output that exceeds the performance objective) until after we conduct a quantitative consequence analysis. Other times, we can make heuristic arguments why a particular model will consistently produce higher releases or doses than another, and we would move forward and analyze the one that produces worst (higher release) results. If both models result in output that exceed the performance objective, then eventually both models would have to be refuted for the site to be deemed acceptable. Consequently, the most robust approach to follow would be to conduct the Monte Carlo analysis described above for each of the alternative models of concern. In some cases, it may be possible to conduct deterministic or limited probabilistic screening analyses to rule out particular models from further consideration.

For most waste disposal regulatory performance objectives, the output distribution represents only our uncertainty in the output and does not include variability in the output. That is, for a given disposal site, there will only be one actual value of total integrated release over the regulatory time period, or one actual value of the maximum dose to an individual, or one actual value of the dose to the average member of a pre-defined group, or one actual value of the maximum concentration in groundwater, etc. Given our state of knowledge, we do not know exactly what the value of that performance measure will be. This implies that given perfect information (perfect knowledge in both space and time), we could define what the performance measure at the site would be.

D. Compliance Evaluation and Assessment Under Uncertainty

This step is critical in defining closure to this process, and if closure is not possible given the current state of knowledge, identifying and prioritizing additional analyses, data collection, or other actions. This evaluation corresponds to Step 6 in the framework (Figure 1).

With the information available to this point, the results of the consequence analysis are evaluated to determine if the site meets the technical regulatory criteria for certification. A defensible decision about certification at this point is possible if the approach used to define scenarios, models, and parameters discussed above has been followed. That is, the analysis should be based on existing information only and should totally account for uncertainty. The approach provides confidence that if additional information were collected, the range of results should narrow or completely shift toward lower values, and the maximum of the distribution should not increase.

If the output from one or more of the models exceeds the performance objective, this does not imply that the site is unacceptable, but rather, given our current state of knowledge we cannot defend certification of the site at this point. Because we have totally accounted for uncertainty coming into this step, there may be value in reducing uncertainty through data collection, such that site acceptance is defensible. This is possible because, once again, if additional information were collected, the range of results should only narrow or completely shift toward lower values, and the maximum of the distribution should not increase. This is a critical point, as the decision to rule out a potentially good site based on the information and level of knowledge at this point would be a mistake. On the other hand, if we get to this point and further reduction in uncertainty is not possible or cost-effective, then the site should not be accepted (this will be discussed under Section 2.5).

In summary, the possible outcomes and decisions that exist at this point are:

- the simulated performance for all models is less than the regulatory criteria and the site can be certified (the process is concluded); or
- the simulated performance for one or more models exceeds the regulatory criteria and possible follow-on actions need to be defined and evaluated (move on to define alternative actions).

E. Reduction of Uncertainty

Data and information collection serves the primary function of reduction of uncertainty. For this process, we evaluate which data could be collected and what value there would be in collecting those data, decide which data to collect, and then actually collect the data we choose (Steps 7 through 10 of the framework). In principle, data collection should never be thought to increase uncertainty, nor can it have any impact on the variability of a population; however, data collection can reduce uncertainty in what the actual distribution of a population is.

To evaluate where to attempt to reduce uncertainty, criteria need to be set to define which parameters or model assumptions are considered important or critical to the compliance decision. Under this framework, for an input parameter or model assumption to be considered important, they must meet the following criteria:

- the uncertainty in the input parameter or model assumption has a significant impact on the uncertainty in the output values (traditional definition of sensitive or important parameter/assumption); and,
- a reduction in the uncertainty would change the decision from fail to pass.

For input parameters, the analyst should also be careful to recognize when the input parameter distribution does include uncertainty (and not simply variability) and data collection activities could actually reduce the range in the distribution.

Figure 2 demonstrates how this process would be implemented for a hypothetical dose requirement where compliance is defined by the mean or the median (whichever is larger) of the output distribution being less than 25 mrem. The entire distribution for Model 1 is below the performance objective. This obviously implies that the mean and the median are also below the performance objective also. Consequently, for Model 1, there is no value in collecting any additional data as the decision of acceptance has already been made and additional data collection under this framework would not change that decision. Therefore, no parameter that is input into Model 1 would be considered important if Model 1 were the only model that remained viable. For Model 3, there is no value in collecting additional data to reduce parameter uncertainty because no amount of reduction in parameter uncertainty would change the decision to refuse the site given Model 3. Again, there are no parameters that are considered to be important in Model 3. However, if data collection could refute certain assumptions (e.g., refute one-dimensional transport and support two-dimensional transport) in Model 3 and shift the entire distribution to the left, then this assumption would be considered important and there may be value in collecting that data.

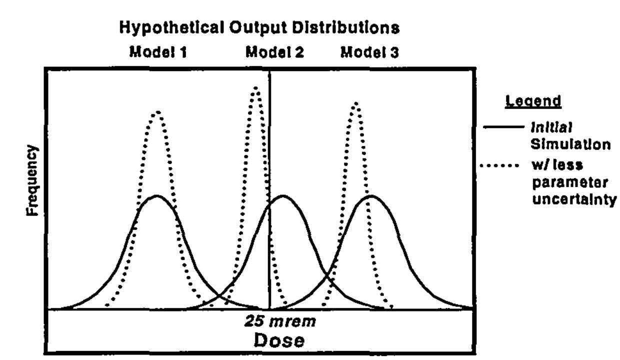

Figure 2 - Dose assessment under uncertainty

Model 2 then becomes the interesting case. If we assume that these output distributions are plotted on a linear scale, then both the mean and the median for Model 2 are initially above the performance objective threshold value.

However, we could demonstrate that if we hypothetically collect data on a particular parameter or set of parameters, that the range in the distribution would decrease and the mean of the distribution would shift to the left, as shown by the broken line. If actual data collection activities supported the hypothesized values, then based on the new model output, the site would be in compliance. The complication for Model 2 comes in when someone else hypothesizes and demonstrates that under a different set of data collection, the range in the distribution decreases, but the mean either remains the same or shifts to the right. Furthermore, if the regulatory requirement is such that the dose objective is for a single member of the population, in the extreme of perfect information, the final output would be a single value somewhere within the current distribution (with the caveat that the Model 2 is "correct"). This creates an obvious conundrum where closure and confidence in the decision are difficult to achieve. A possible solution to this is to make the decision of compliance based on the 0.95 quantile or maximum value of the distribution rather than the mean or median because in any of these cases under this framework, the maximum could only stay the same or decrease.

Note that *actual* reduction of uncertainty would not be realized until the completion of Step 10 in the framework. Therefore, the exercise that has been conducted to this point is defining what would be required for success under the given data collection activity, evaluating the chances of that activity being successful, and evaluating the cost of that activity relative to other options at the site. If the likelihood of success for a given data collection activity is very low, or if the cost is relatively high, then remediation or some other option may be the best alternative.

F. Termination of process

Termination and closure of this process under this framework is defined in one of two ways:

- the results from all models are less than the performance objective threshold values (i.e., with confidence, we can say that the site is acceptable), or
- the results from one or more of the models exceed the performance objective threshold values, and either reduction in uncertainty would not result in compliance or it is relatively too costly to conduct the activities necessary to get to compliance (i.e., with confidence we can say that the site is not acceptable or we do not have enough money to confidently demonstrate acceptability).

III. APPLICATION OF THE PROCESS AT THE GREATER CONFINEMENT DISPOSAL SITE

The U.S. Department of Energy is responsible for the disposal of a variety of radioactive wastes. Some of these wastes are prohibited from shallow land burial and also do not meet the waste acceptance criteria for proposed waste repositories at the Waste Isolation Pilot Plant (WIPP) and Yucca Mountain. As a result, these wastes require an alternative disposal method. From 1984 to 1989, the Department of Energy disposed of a small quantity of such transuranic wastes at the Greater Confinement Disposal (GCD) site at the Nevada Test Site. For the GCD waste to remain emplaced and be considered permanently disposed of, performance assessment results must show compliance with the Environmental Protection Agency standards for disposal of transuranic waste, high-level waste, and spent fuel (40 CFR 191).[5]

A. Regulatory Environment and Requirement for Treating Uncertainty

In terms of the regulatory environment, the performance of the GCD facility is compared against the EPA regulation for disposal of spent fuel, transuranic waste, and high-level waste, 40 CFR 191.[5] The overall objective of the performance assessment analysis is, simply stated, to provide the DOE with the technical basis to make a decision regarding regulatory compliance in the most efficient way possible. As a result, an implicit objective of the process is to use the regulatory performance measures to focus model development and data collection and to define when further data collection has no value.

The regulation (40 CFR 191) contains three quantitative requirements: containment, individual protection, and groundwater protection. The containment requirements are probabilistic in nature. That is, they limit the probability of certain levels of cumulative or integrated releases, in terms of curies, of radionuclides to the accessible environment over a period of 10,000 years. The accessible environment is defined to include the ground surface and any point in the subsurface that is laterally beyond five kilometers from the disposal site. The allowable cumulative release for each radionuclide is based on the initial inventory for that radionuclide. The normalization or scaling factors are the release limits listed in 40 CFR Part 191 and define the number of curies of a given radionuclide that can be released per curies of initial inventory of that radionuclide. The "EPA Sum" is calculated by first computing the ratio of the simulated release estimates for each radionuclide to the allowable release estimate and then summing these ratios. The containment requirements state that the EPA Sum must have a likelihood of less than one chance in 10 of exceeding one and a likelihood of less than one chance in 1000 of exceeding 10. In other words, the 0.9 quantile of the output distribution of EPA Sum cannot exceed one, and the 0.999 quantile of the output distribution cannot exceed ten. By this definition, the regulation implies that explicit treatment of uncertainty and/or variability is required. Furthermore, the treatment of uncertainty is necessarily probabilistic; that is, a deterministic analysis would not provide the information needed to estimate the 0.9 and 0.999 quantiles of the output distribution and therefore would not provide a basis for decision making.

As a result of these requirements, the final quantitative output of the performance assessment calculations is a distribution of possible outcomes. This output distribution represents the range in the magnitude of possible outcomes and the probability of each of those outcomes. For 40 CFR 191, the performance measure for the containment requirements is typically displayed as complementary cumulative distribution function (CCDF), which is a stepwise, monotonically decreasing function (i.e., a function where f(x) never increases as x increases) that is plotted with probability of exceeding various levels of the performance measure on the vertical axis and the performance measure (EPA Sum) on the horizontal axis. The CCDF is the complement of the integrated sum of output values. Bonano and Wahi[12] provide a more comprehensive discussion on the construction and interpretation of a CCDF. Hypothetical CCDF curves can be found in Figure 3. When the output distribution is plotted in this way, a CCDF that passes through the shaded region in Figure 3 indicates a violation of the EPA's containment requirements while one that does not pass through the shaded region indicates compliance with the requirements. For the individual protection and groundwater, the output from a probabilistic analysis may be presented as a histogram of possible results, a cumulative distribution function, or as a CCDF.

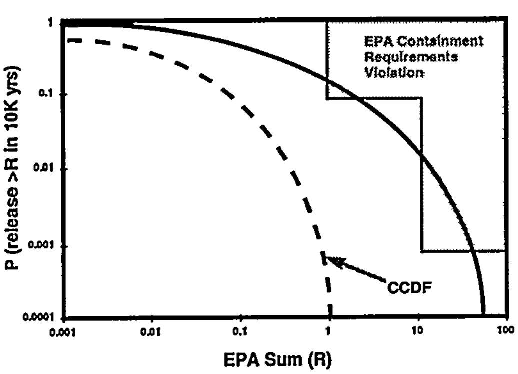

Figure 3 - Hypothetical 40CFR 191 CCDFs

All three of the quantitative requirements in 40 CFR 191 (containment, individual protection, and groundwater protection) require that the system design and the analyses pro vide a "reasonable expectation" that the performance objectives will be met. EPA[5] states that "this phrase reflects the fact that unequivocal numerical proof of compliance is neither necessary nor likely to be obtained." Our interpretation of reasonable expectation is that, given the uncertainty in the analyses, the likelihood of making an incorrect regulatory decision should be very low, but guaranteeing that the site will not exceed the performance objectives is impossible.

B. Specific considerations for the GCD site

There exist some considerations that are specific to the GCD site that place constraints on the alternative actions that might be taken at this site. These include:

- the waste at GCD has already been placed in the ground and the disposal units have been backfilled;
- the inventory of waste is fixed, for all practical purposes;
- because the waste has already been disposed of, there are fewer disposal facility and packaging design options that exist than if the waste was above ground today;
- the top of the waste in the GCD boreholes is approximately 70 ft. from the land surface and the bottom is several hundred feet above the water table, perhaps making surficial processes relatively more important than processes that move contaminants downward;
- there are other waste types physically located immediately adjacent to and above the GCD TRU wastes.

In general, these considerations do not have an impact on how we would treat uncertainty for this system. Rather, they place certain constraints on the possible alternative actions that might be taken at this site. For instance, there no longer exists the opportunity to alter the magnitude of the source inventory, waste chemistry, disposal depth, or site location. Additionally, if the assessment indicates the site will not meet the performance objectives, then the alternative actions are remediation by moving the waste to a different site or configuration, or pursuit of an alternative compliance strategy.

C. Applying the approach to the individual and groundwater protection requirements

The containment requirements, by their definition, require evaluation within a probabilistic framework. The individual protection and groundwater protection requirements, are not defined probabilistically, but rather define deterministic threshold values that must be met. Despite deterministic performance objectives, a probabilistic approach is still applicable as long as the level of confidence or acceptable probability of failure is specified *a priori.* For the individual and groundwater protection requirements in 40 CFR 191[5], the EPA "assumes that compliance can be determined based upon 'best estimate' predictions (e.g., the mean or median of the appropriate distribution, whichever is higher)." For the individual protection requirements for example, if the median of the distribution were used for compliance assessment, this would be the equivalent of stating that the dose must have a likelihood of less than one chance in two of exceeding 25 mrem. The recommendation that the mean or median of the output distribution be used for compliance determination implies that quantitative probabilistic statements will be necessary to address these regulatory requirements.

D. Treatment of Uncertainty for GCD

EPA's 40 CFR 191 requires that all sources of uncertainty be included in a performance assessment. Under this regulation, we are dealing with the performance of a natural system over 10,000 years for the containment requirements and 1,000 years for the individual protection and groundwater protection requirements. We are also evaluating the performance over several kilometers. Consequently, we expect to have much uncertainty about how the system will behave and respond to specific disturbances.

1. Uncertainty in the Likelihood of Occurrence of Future Events

EPA's 40 CFR Part 191 also requires analysis of "all significant processes and events that may affect the disposal system".[5] Therefore, all plausible future states of the disposal system, called scenarios, will be considered in a performance assessment for GCD. For our methodology, each scenario represents one of the possible combinations of plausible events and processes at the given site over 10,000 years. Methods for developing and screening scenarios that each describe a plausible future state of the disposal system in a way that satisfies the requirements under 40 CFR 191 have been addressed by Cranwell *et al.*[13] The definition of *plausible* in this case means that an event or a scenario has a probability of greater than one chance in 10,000 of occurring in 10,000 years (i.e., annual probability of greater than 10^{-8}).[5]

Basically, scenarios are developed by defining all the possible combinations of events that could have impact on the site's performance. The probability of an event represents the likelihood that the specified event will occur at the site over the regulatory time period of 10,000 years. The probability of a scenario represents the likelihood that all the events within that scenario will occur over 10,000 years. The probability is calculated as the product of the probabilities of each of the events and/or non-events that comprise the scenario. A probability of occurrence is estimated for each scenario so that the consequence of every scenario can be folded into a single CCDF.

2. Uncertainty in Models That Describe Events and Processes

Conceptual model uncertainty has been represented in the GCD performance assessment using multiple models. These uncertainties include whether advection or diffusion is the dominant transport mechanism under the current conditions, and whether or not climate change will occur during the regulatory period and the consequences if it does. Preliminary analyses indicated that the significant conceptual model uncertainties (those that might cause violation of the containment requirements) were the direction of contaminant transport (to the ground surface with steady diffusion or to the water table with steady recharge) and the potential recharge rate due to changes in climatic conditions.

These results led to site characterization activities that indicated there is no recharge under the existing climate conditions and that a climate change greater than the last glacial maximum is necessary to cause aerially distributed recharge. Models are currently being developed to provide more detailed simulations of the upward movement of contaminants.

3. Uncertainty in Parameter Values

Physical limits, the results of laboratory and field studies, site characterization activities and models have been used to bound the uncertainty and various pdfs have been used to represent in the GCD performance assessment model parameter values. The initial parameter values and pdfs were based on the existing site information and information from analogous situations. The parameter values are being updated for the new transport models and revised based on site characterization data.

4. Propagation of Uncertainty

For the GCD performance assessment analyses, Monte Carlo simulation has been used to propagate parameter uncertainty through models to results of analyses. As stated above, this results in a suite of possible outcomes. That is, if we have 100 samples, then each value of the performance measure is treated as if it has a probability of occurrence of 0.01. For the containment requirements, these are then conditioned on the probability of the scenario that they represent. Therefore, the probability of a given outcome becomes the probability of the random sample multiplied times the probability of the scenario. For the individual and groundwater protection requirements, probability of scenarios does not come into play, as disruptive events beyond existing conditions are not considered (as specified by the regulation).

To propagate and address uncertainty in conceptual models, multiple alternative conceptual models have been developed and evaluated. All of the models that result in output that exceeds the performance objectives were carried forward in the analysis.

For the regulatory performance objective of total integrated release, the output distribution represents only our uncertainty in the output and does not include variability in the output. That is, for the GCD site, there will only be one actual value of total integrated release over the next 10,000 years. Given our state of knowledge, we do not know exactly what the value of that release will be. It turns out that this is true for dose and concentration performance measures also. Again, there will only be one maximum dose at a given site over the next 1,000 years and again, we do not know exactly what that dose will be. This implies that given perfect information (perfect knowledge in both space and time), we could define what the total integrated release at the site would be. Given perfect information we could also determine what the variability in doses would be across the affected population; however, because we are interested in the dose to *any* member of the public, we would rule on the maximum value of that distribution, which is a single value.

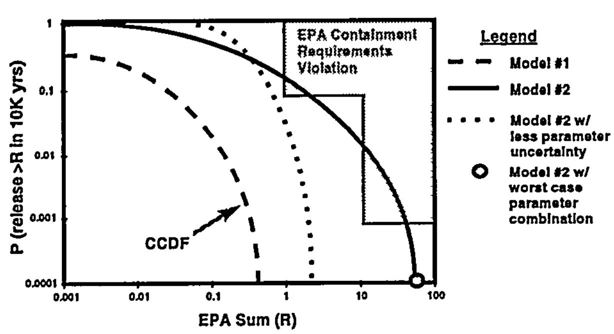

Figure 4 - CCDFs and reduction of uncertainty

5. Compliance Evaluation and Assessment Under Uncertainty

With the information available to this point, the results of the consequence analysis are evaluated to determine if the site meets the criteria for release. Under 40 CFR 191, this would mean that the CCDF does not pass through the shaded region in Figure 4. In Figure 4, hypothetical Model 1 shows compliance with the containment requirements, whereas Model 2 initially does not show compliance. The broken line in Figure 4 illustrates how the CCDF for Model 2 could change if there were a reduction in parameter uncertainty given this model. If the results from both models were to the left of the shaded region, and no other models could be defended that would produce higher results, then technically the site would be in compliance with the containment requirements and no additional work should be required to defend the results.

6. Reduction of uncertainty

To date, the results of the preliminary analyses have been used to identify and justify additional data collection and model development. Site characterization data have reduced the conceptual model uncertainty and the uncertainty in several key parameter values (recharge rate, plutonium solubility and distribution coefficient, and tortuosity). Additional models have been developed and the complexity of the model of transport of contaminants from the waste to the ground surface have been developed. Depending on the simulation results with these updated models and parameter values, future activities could be identified to further reduce the uncertainties or increase the complexity of the modeling (i.e., decrease the number of simplifying assumptions).

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