Improving Site-Specific Radiological Performance Assessments - 13431

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ABSTRACT

An improved approach is presented for conducting complete and defensible radiological site-specific performance assessments (PAs) to support radioactive waste disposal decisions. The basic tenets of PA were initiated some thirty years ago, focusing on geologic disposals and evaluating compliance with regulations. Some of these regulations were inherently probabilistic (i.e., addressing uncertainty in a quantitative fashion), such as the containment requirements of the U.S. Environmental Protection Agency's (EPA's) 40 CFR 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*, §191.13 [1]. Methods of analysis were developed to meet those requirements, but at their core early PAs used "conservative" parameter values and modeling approaches. This limited the utility of such PAs to compliance evaluation, and did little to inform decisions about optimizing disposal, closure and long-term monitoring and maintenance, or, in general, maintaining doses "as low as reasonably achievable" (ALARA). This basic approach to PA development in the United States was employed essentially unchanged through the end of the 20th century, principally by the U.S. Department of Energy (DOE). Performance assessments developed in support of private radioactive waste disposal operations, regulated by the U.S. Nuclear Regulatory Commission (NRC) and its agreement states, were typically not as sophisticated. Discussion of new approaches to PA is timely, since at the time of this writing, the DOE is in the midst of revising its Order 435.1, *Radioactive Waste Management* [2], and the NRC is revising 10 CFR 61, *Licensing Requirements for Land Disposal of Radioactive Waste* [3].

Over the previous decade, theoretical developments and improved computational technology have provided the foundation for integrating decision analysis (DA) concepts and objective-focused thinking, plus a Bayesian approach to probabilistic modeling and risk analysis, to guide improvements in PA. This decision-making approach, [4, 5, 6] provides a transparent formal framework for using a value- or objective-focused approach to decision-making. DA, as an analytical means to implement structured decision making, provides a context for both understanding how uncertainty affects decisions and for targeting uncertainty reduction. The proposed DA approach improves defensibility and transparency of decision-making. The DA approach is fully consistent with the need to perform realistic modeling (rather than conservative modeling), including evaluation of site-specific factors. Instead of using generic stylized scenarios for radionuclide fate and transport and for human exposures to radionuclides, site-specific scenarios better represent the advantages and disadvantages of alternative disposal sites or engineered designs, thus clarifying their differences as well as providing a sound basis for evaluation of site performance.

The full DA approach to PA is described, from explicitly incorporating societal values through stakeholder involvement to model building. Model building involves scoping by considering features, events, processes, and exposure scenarios (FEPSs), development of a conceptual site model (CSM), translation into numerical models and subsequent computation, and model evaluation. These are implemented in a cycle of uncertainty analysis, sensitivity analysis and value of information analysis so that uncertainty can be reduced until sufficient confidence is gained in the decisions to be made. This includes the traditional focus on hydrogeological processes, but also places emphasis on other FEPSs such as biotically-induced transport and human exposure phenomena. The significance of human exposure scenarios is emphasized by modifying the traditional acronym "FEPs" to include them, hence "FEPSs".

The radioactive waste community is also recognizing that disposal sites are to be considered a national (or even global) resource. As such, there is a pressing need to optimize their utility within the constraints of protecting human health and the environment. Failing to do so will result in the need for additional sites or options for storing radioactive waste temporarily, assuming a continued need for radioactive waste disposal. Optimization should be performed using DA, including economic analysis, invoked if necessary through the ALARA process. The economic analysis must recognize the cost of implementation (disposal design, closure, maintenance, etc.), and intra- and inter-generational equity in order to ensure that the best possible radioactive waste management decisions are made for the protection of both current and future generations. In most cases this requires consideration of population or collective risk.

INTRODUCTION

Radioactive waste disposal is a challenging problem around the world. Compounding the challenge is the lack of a consistent and well-founded technical approach to PA, which leads to confusion and distrust among stakeholders, and inefficient use of limited disposal resources among site operators. A conceptually simple framework for site-specific radiological PA is needed—one that takes into account site characteristics that influence performance metrics, and that recognizes uncertainties inherent in the engineered, environmental, physiological, and social systems that are analyzed. A clear definition of the metrics by which system performance is judged, which should be aimed at maximizing benefit to societal welfare as opposed to aiming merely at compliance, is also needed. This paper discusses the attributes of such a framework.

Regulatory Context

Near-surface disposal of low-level radioactive wastes (LLW) is regulated in the United States by two principal federal regulations, the U.S. Department of Energy (DOE) Order 435.1, *Radioactive Waste Management* [2], and the U.S. Nuclear Regulatory Commission (NRC) 10 CFR 61, *Licensing Requirements for Land Disposal of Radioactive Waste* [3]. While this discussion focuses on near-surface burial of LLW, it is equally relevant for the disposal of other radioactive wastes, including uranium mill tailings, transuranic waste (TRU), high-level waste (HLW), used or spent nuclear fuel (SNF), and orphaned "no path forward" wastes such as Greater-Than-Class-C (GTCC) waste, its DOE counterpart GTCC-like waste, and depleted uranium (DU). The overall approach does not differentiate between types of waste. It is aimed instead at optimization of waste management decisions as guided by the site-specific need to protect human health and the environment and to satisfy the concerns of the various stakeholder groups. Such an approach may allow the relevant regulations to be simplified, which would make the process of PA and associated decision making easier to address.

The Traditional Performance Assessment Process

For the purposes of this discussion, the focus is on PA of near-surface burial of LLW, but the same basic principles apply to radioactive waste management generally. These LLW PAs have typically been deterministic and conservatively biased, even though conservatism is often difficult to judge. PAs for geologic disposal, such as those performed for the Waste Isolation Pilot Plant and the Yucca Mountain Project, are probabilistic and already incorporate some of the methods proposed here. However, probabilistic contaminant transport modeling in these PAs was conducted within a framework of conservative assumptions for land use and human activities. The standard of LLW PA practice continues to evolve, changing from a conservative, stylized, and deterministic approach to a more realistic, site-specific, and probabilistic approach. The traditional approach is summarized here in order to provide background for the discussion of a proposed approach to PA that elevates its role in decision making.

The principal motivation for performing PA in the latter part of the 20th century was to evaluate compliance of existing radioactive waste disposal sites (some closed and some still operating) with then current regulations. Little emphasis was placed on optimal use of the sites. This limited perspective resulted in the desire to model sites conservatively; i.e., to err on the side of increasing modeled doses via presumed dominant contaminant transport and exposure pathways in the interest of public safety.

Because the discipline of PA grew out of the science of hydrogeology, the presumed contaminant transport pathways of greatest significance involved groundwater, though other pathways sometimes included the diffusion of radon out of the disposal facility into the atmosphere. To a limited extent, the consequences of inadvertent human intrusion into the waste were also examined. However, these analyses were not coupled to the computational assessment of radionuclide transport. Instead, stylized scenarios (e.g., using a "reference man", drilling a water well through waste, etc.) have been employed in PA, and in many cases these are required by regulation [2,3]. Thus, the scoping of a given PA was limited by preconceptions of which contaminant transport mechanisms would be significant and of the nature and consequences of future human activities. This approach may serve to demonstrate compliance of a closed waste site with regulatory standards, but it is not useful for operating an existing site, nor is it useful for selecting remedies for a site that is out-of-compliance. It is also not a useful approach for optimizing disposal, closure and long-term monitoring and maintenance, and thus for making the best use of these national resources. In short, the approach is poor for informing optimal decision making.

In early PAs, modeling methods were deterministic and oriented towards presumed conservatism for a number of reasons. One reason to be conservative was to avoid the problem of not being able to adequately represent uncertainty—a very conservative result at least would bound uncertainties in one direction. This was considered necessary because of the computational burden of the traditional approach to modeling, and the computational complexity at the time of building a probabilistic model. Typically, detailed "process level" computational models were built by experts in different disciplines, using specialized computer programs. Results from each sub-model would then be linked together. For example, one model might start with estimates of release from a waste form. Results from the waste release model would be fed into a groundwater transport model, which would provide radionuclide concentrations at a water supply well. A separate model might be used to estimate diffusion of radioactive gases such as radon at the ground surface. These models would feed calculated exposure media concentrations into a human exposure model in order to estimate future doses. Each model was designed to be conservative in its calculations, erring on the side of greater release and transport rates, greater water concentrations, and greater exposure rates. In some cases, two competing pathways, such as groundwater transport and gaseous diffusion, would both employ worst case assumptions that were mutually exclusive, effectively creating physically implausible and thereby indefensible, models of the environmental system, and double-counting exposures. Conservatism is compounded within inventory reporting, contaminant transport models, exposure models and the choice of metric used to evaluate compliance. This "conservatism on top of conservatism on top of conservatism" does not support good decision making. It provides a distorted view of the likely performance of a candidate waste disposal site. It is also perhaps no surprise that it becomes difficult to communicate a PA to the public and other stakeholders when the models presented do not follow a reasonable semblance of common sense.

These conservative and deterministic fate and transport models were input into default stylized exposure models that represented "members of the public" (MOP) and "inadvertent human intruders" (IHI). These stylized scenarios were based on the concept of a "reference man", and generally do not represent current or future behaviors or societal conditions at a site. This traditional approach to dose assessment has also been focused on dose to individuals. For compliance evaluation, these doses are evaluated against performance objectives only for the worst-case year, according to the results of the models. This might be reasonable for compliance, but does not support optimization of radioactive waste management. Focusing on the worst-case year adds a further layer of conservatism for remotes sites at which the very presence of a receptor, whether an MOP or IHI type of receptor, is uncertain. Locations for radioactive waste disposal are spread across the United States (and the world), with varying conditions. The most favorable natural conditions, however, tend to be in the remote and inhospitable arid or semi-arid systems such as those found in the American west. In some cases the areas in which radioactive waste management sites are located do not have a history of human presence. Further, the groundwater is non-potable at some sites. Nevertheless, traditional dose assessment for PA assumes that receptors are present at all times, and that water well drilling will occur. These sites were chosen in large part because of their location away from population centers, and this attribute should be used to distinguish between sites. This requires not only an individual risk (dose) assessment, but also a population risk (dose) assessment, for which in both cases, the modeled receptors are representative of the best current understanding of societal conditions at a site.

Evaluation of site performance was thus based on preconceived notions of which contaminant transport mechanisms are important and on preconceived exposure scenarios. This type of approach may have been reasonable when the NRC and DOE regulations were first written, but computational capability has changed appreciably and the scientific process of risk assessment has gained 40 years of experience. It is very reasonable to think that the improved knowledge and technological approaches should be used in PA in a paradigm shift that takes advantage of what has been learned in the past 40 years.

Traditional PA modeling has focused on contaminant transport, and has not paid attention to important factors such as exposure modeling, inventory estimation, and population risk (dose) to support decision making. The paradigm shift that is needed is towards a DA or risk management approach to evaluating performance of radioactive waste disposal. This approach would require site-specific models for inventory, source release, and contaminant transport, that are coupled with reasonable site-specific exposure scenarios, and are evaluated using some decision metrics that evaluate cost-benefit. This DA-based approach would rely on objective modeling of the disposal system. This does not preclude making a conservative decision. That should depend on the stakeholders' preferences and desires, again from a site-specific perspective. It also requires economic modeling of the disposal system to include cost, environmental, and societal factors. The decision model should be used to drive the need for research and model refinement through sensitivity analysis and value of information analysis with the goal of effectively reducing uncertainty. Such a paradigm shift might not be easy initially, as it requires a shift towards system-level decision modeling so that the waste management problem can be solved effectively, with the need for more complex (process-level) modeling identified by the behavior of the system-level model. This approach requires stakeholder involvement throughout, including the interested public, and is easier to communicate because it is based on a reasonable common sense approach to addressing the technical issues. It is site-specific, represents what is currently known or understood while projecting that knowledge about the natural and engineered systems and human society into the future, and bounds the future through consideration of the potential impacts on possible future populations. Decision making can still be conservative, but the supporting modeling should not be. How this might be accomplished is described in the next section.

The Proposed Performance Assessment Process

The proposed PA approach takes advantage of decades of experience with PA work, and of much-improved computational power and programs. It also involves a fundamental paradigm shift from initial detailed, process-level modeling that has been traditionally focused on compliance evaluation, to initial system-level modeling focused instead on effective use of radioactive waste disposal facilities, and supported by more detailed models only where needed. This is a more efficient approach for getting to the desired result: a defensible, relevant, model that effectively supports decision making for disposal, closure, and long-term monitoring and maintenance—i.e., for radioactive waste management.

The basic theory behind this approach is to use DA to support the program. Essentially, DA is formalized common sense, so philosophically it is simple to communicate. It is an approach to organization of models that is fully inclusive of stakeholder values and potential consequences of actions that might be taken (disposal, closure, etc.). It requires stakeholder involvement throughout so that the models are owned by the stakeholders; the modeling paradigm is simply an evaluation tool for solving a complex problem. It is aimed at optimization in the context of maximizing societal welfare, and hence includes cost-benefit or economic analysis as integral components of the system. Decision analysis as an approach can be invoked easily through ALARA, which requires keeping doses as low as reasonably achievable.

Stakeholder involvement is critical from the beginning so that the decision model structure and specification is agreed upon up front. With this approach, the results are a consequence of the model and any data and information that is collected. Results cannot be challenged except through the model structure and its specification. This provides a much more open, transparent and defensible approach to modeling and decision making. Iteration is driven by the uncertainty in the decisions that might be made; i.e., if more information is needed to reduce uncertainty, then it should be collected. DA provides a formal approach for addressing the need for more data through formal global sensitivity analysis and value of information analysis. As more data are collected the model is refined or improved, and uncertainty in the final decisions is reduced.

There are several steps that are taken in a DA:

1. Identify objectives and decision options.
2. Build a model with available information (probabilistic model for the technical aspects and cost/value judgment models for the economic analysis components).
3. Evaluate the model through uncertainty analysis.
4. Determine if the decision can be made or if more data and information are needed.
5. Perform sensitivity analysis and value of information analysis if necessary and iterate.

Objectives and decision options (disposal, closure, etc.) are identified and are used to define the DA. Assumptions, uncertainties and value judgments are clearly communicated through active stakeholder engagement throughout. As noted, the concept is to use DA methods to formalize what is thought to be known about a problem and the uncertainties about what is thought to be known. However, because the approach is a top-down system-level approach, DA modeling should be "as simple as possible, but no simpler" [7]. For example, there is no need to perform complex, process-level, groundwater modeling at a site that has no potable groundwater, or no pathway to groundwater. DA helps "keep the eye on the prize", i.e., defensible and cost-effective problem solving.

The basic goal of DA is, in the long run, to choose the decision option that yields the best expected outcome, given what is known or believed about the system, and given costs and value judgments related to the economic, environmental, and societal impacts of the decision. For example, the overall objective may be to maximize societal welfare, or find the decision option that is best overall. Figure 1 provides a high-level overview of the DA cycle.

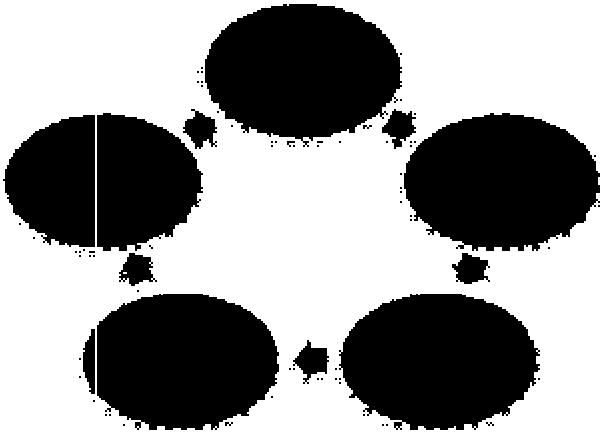
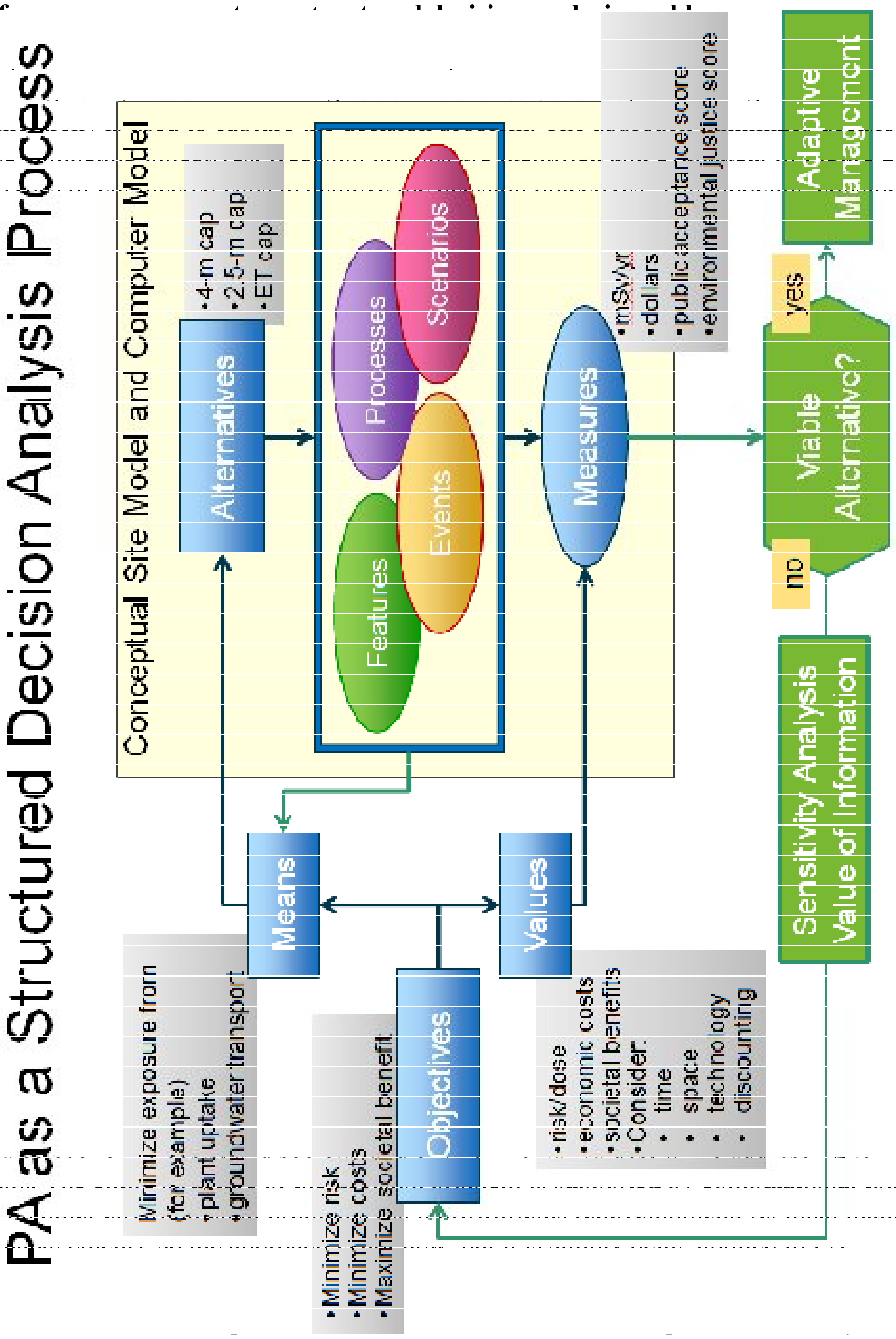


Fig. 1. The decision analysis cycle.

Figure 2 provides a high-level DA approach that can be used to focus radioactive waste management problem solving. Figure 2 identifies the roles, and hence importance, of scoping the problem (for example using an analysis of features, events, processes, and human exposure scenarios, or FEPSs) as part of building a CSM, which, in turn is structured into a numerical model for evaluation. These components are most familiar in the context of traditional PA. The DA model, however, sets the stage for an approach to CSM development that is embedded within the decision framework.

Fig. 2. Per



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groundwater or infiltration modeling in all cases. Site-specific receptor scenarios, or value judgments of the site-specific stakeholders, may be more important in some or many cases.

Using this approach, decision making is supported by DA. This approach is open, transparent and provides defensible solutions to the radioactive waste management problem. However, many of the basic tenets of traditional PA are apparent. The focus has shifted to realism rather than conservatism, but otherwise components of traditional PA are still an integral part of the system. The following list highlights components of PA that need to addressed in more integrated and defensible ways to support the DA approach:

1. If a PA of a radioactive waste disposal facility is to be useful in decision making, it must provide a sufficient understanding of the site so that stakeholders are confident that all relevant processes have been considered. Stakeholders need to be involved in the process so that they will gain confidence in the site and the PA, which is the most detailed representation of the site. Ultimately, the public is likely to "own" all radioactive waste sites, either by intention or by default. By including all interested parties in the process, and through open communication and model transparency, credibility and trust can be gained so that unreasonable opposition will dissipate.

2. Scoping of the PA is driven by the decision objective and options. In this context a broader view should be considered regarding which processes could be relevant. Earth science disciplines such as hydrogeology, hydrology, and meteorology are still considered of course, but additional FEPSs are drawn from biology and the social sciences. Identification of FEPSs should be expanded to include demographics and human behaviors, as these are integral to the modeling endpoints for risk to future humans. To that end, land use scenarios and human exposure scenarios should be added to the analysis. Hence the change from the traditional "FEPs" to "FEPSs". Included in the FEPSs should be all the site-specific phenomena affecting site stability, fate and transport of contaminants from wastes to exposure media, human behaviors leading to exposure to those media, and physiological responses to radiation. Constructing FEPSs frames the site-specific PA analysis, and to the extent that it is thorough, assures that no important issue is omitted.

3. The FEPSs should still be used to construct CSMs, but not with just a single CSM deliberately constructed to favor a conservative result. A CSM should reflect what is thought to be known about a site. The objective of this approach is to model objectively and with realism. Decisions that are protective of public safety can then be made objectively, transparently, and defensibly from a realistic PA model, instead of making decisions based on unrealistic conservative models. Several competing CSMs can also be considered, so that the uncertainty inherent in conceptualization of the problem may be evaluated and used to inform decision making.

4. The basic structure of a PA model should be different from the traditional one of several detailed processes models linked together. Instead of that style of "bottom-up" modeling, the approach should be "top-down" An initial model should be designed to capture the essential elements of one or more CSMs, as developed following a thorough scoping analysis. These essential elements should be constructed and related using simple and perhaps coarse sub-models, rather than detailed ones. Only later are parts of the initial model developed in greater detail, as guided by their relative importance that emerges from an ongoing analysis of the model results. The goal of this approach is to have a model that is sufficiently well developed in those areas that are important to determining model endpoints. Other parts of the model, which are not of great importance in determining these informative results, are left relatively undeveloped. This process will optimize the removal of uncertainty in the model, and will increase its defensibility in key areas. Model development then iterates until the decision being made is sufficiently supported.

5. Concurrent with model structural development is the specification of model input parameters. These should be defined stochastically at the outset, to the extent that they are uncertain. While some model inputs have very little uncertainty (e.g. the value of the half-life of a given radionuclide) many more are

much less well known. The specification of these values should reflect the state of knowledge about them; i.e. parameter uncertainty. As the model matures via iteration and successive examination of results, those parameters that are most important to the results are identified, and the uncertainty represented in these sensitive stochastic parameters is scrutinized. As the uncertainty in sensitive stochastic model inputs is reduced, so is the uncertainty of the overall model results reduced.

6. The process of transparent iteration in site-specific PA model development is critical to its defensibility. Bayesian methods provide a rigorous formal framework for model updating as more information and data are collected. Use of Bayesian methods in the DA approach supports a top-down modeling process in which initial probabilistic model development is based on information at hand and professional judgment. Initial probabilistic modeling can be updated using a Bayesian approach that merges prior information and subsequent information and data collected weighted by the information content. The Bayesian approach also provides a natural framework for value of information analysis to identify the optimal path forward given the information content of the current state of analysis and stakeholder values.
7. The metric that can or should be applied to evaluate performance using the proposed DA approach is one of risk (be it expressed as effective dose equivalent, or organ dose, or whatever metrics are chosen) to a population of hypothetical future receptors. Risk is much more intuitive than dose, and the value of risk reduction can be evaluated in a direct sense in a DA structure.
8. In the context of radioactive waste disposal, decision makers are asked to consider human health effects into the distant future. A matter of current debate is the appropriate length of time that future doses should be considered for decision making. While traditional approaches to this aspect of decision making have weighted the values of future generations and of the current generation equally up until some compliance period threshold, this is not necessarily in keeping with economic theory and experimentation. Humans tend to value the near future and its inhabitants over the distant future, as evidenced in environmental regulations for chemicals other than radionuclides (e.g., the Comprehensive Environmental Response, Compensation, and Liability Act – CERCLA, and the Resource Conservation and Recovery Act – RCRA). The proposed DA approach for PA includes the capacity to include ‘discount functions’ as part of an economic analysis that would account for the long-term consequences of radioactive waste disposal. The calculation of risk could be modified to take account of generational equity issues, from which a time period of concern will naturally emerge, possibly site-specifically. Specification of discount functions should be performed site-specifically to take into account the values of all relevant stakeholders. This should be performed using a formal decision structuring process [4]. If discount functions are employed, the time of peak concern might be sooner in time than the millennia that are currently considered in radioactive waste disposal regulations. Discounting is not the only financial aspect of a DA that should be considered. Discounting is part of a financial analysis that is needed for long-term radioactive waste management, which should also include the need for an evaluation of long term financial assurance (e.g., trust funds), insurance mechanisms, interest rates, etc., for a complete economic analysis as part of the proposed cost-benefit analysis or DA.

The purpose of this DA approach to PA is to facilitate effective decision making, and to provide a more complete risk management analysis of a radioactive waste disposal site. Inclusion of economic components in the analysis could lead to more effective consideration of the long-term future of a radioactive waste disposal system, and consequent decision actions that need to be taken for long-term success. This analysis would also consider long-term factors other than human health risk (dose) if they are deemed important for a site, including climate change, volcanic activity, meteor strikes, etc. This DA approach can be used to address site-specific decisions regarding disposal options for given waste streams, closure options for a disposal facility, and long term monitoring and maintenance decisions that ensure that resources are applied to the most important needs of this complex decision making process.

Realism and Conservatism: Uncertainty and Probabilistic Modeling

As briefly discussed above, model development can be centered around conservative approaches, around realistic approaches, or around a mix of these. It can also be built around probabilistic models or deterministic models. Often conservative approaches are associated with deterministic models and realistic approaches are associated with probabilistic models. Conservative modeling in highly non-linear systems such as those modeled in PA can be fraught with unintended consequences, and can result in appreciable deviations from reality. Realistic models are perceived as being more challenging to construct, as they require more careful definitions of models and parameters. However, the benefit is that the additional effort will provide greater insight into site performance.

A common example or unrealistic modeling is the conservative assumption of large infiltration rates and low soil/water partition coefficients, employed in order to flush radionuclides from the waste to an aquifer that is presumed to serve as a drinking water supply. This removal of radionuclides from the wastes, however, would reduce the availability of radionuclides for upward contaminant transport pathways (e.g. diffusion and biotically-induced transport), and would diminish exposures to a future intruder who would be exposed to exhumed wastes. There is no single set of circumstances or assumptions that is conservative for all scenarios. A better approach is to assign uncertain yet unbiased values to input parameters that are relevant to the process of infiltration and soil/water partitioning, so that a natural range of cases is considered. Further, the probabilities of occurrence of the act of drinking from the aquifer or exhuming waste should also be considered in the analysis. Only with these uncertainties built into the model can the relative importance of such “competing” scenarios be evaluated.

Model uncertainties can be evaluated in a DA approach. An example is the representation of tortuosity. There are several mathematical models for representing both air-phase and water-phase tortuosity in the literature, and unless site-specific tortuosity estimates have been made, a modeler is faced with choosing between these various mathematical representations. One approach is to include them all, and select between them at random during the building of realizations. Another example of mathematical model uncertainty is in the common use of the linear soil/water partition coefficient model, commonly known as K_d. Use of this simple model for chemical partitioning of a chemical between porous solids and water is ubiquitous, even though the geochemical community considers it a misleading oversimplification. Similarly, the linear no-threshold dose model that is inherent in assumptions regarding radiation risk (focused on cancer) is an oversimplification, with little basis at the low concentrations that are experienced in the vicinity of radioactive waste sites. This is commonly represented in PA modeling as a constant dose conversion factor (DCF), linearly related to exposure media concentration. These mathematical representations of important phenomena should be viewed with skepticism, and alternative representations should be considered.

The limitations of simple linear models like K_d or DCF are sometimes addressed by the introduction of uncertainty in the parameterization of the model. In the case of K_d, a range of values used in the linear model attempts to make up for the possibility that the model is not actually linear. The same could be said of the radiation risk (DCF) model, but there has been reluctance in the PA community to consider uncertainty in radiation risk. Recent work, however, has opened the door to addressing uncertainty in dose (and therefore risk) calculations [8].

Uncertainty representation is a natural part of DA that corresponds to probabilistic modeling in which uncertain inputs are represented as probability distributions in the PA modeling. A vital component of specifying input probability distributions is carefully specifying input covariance structures. Another component of probabilistic modeling that is often overlooked concerns correlation. Correlation (or covariance) matrices are difficult to specify in PA modeling programs. However, it is possible and it can be very important. Physical properties, for example, should be correlated. If they are not, then the inverse effect of porosity and bulk density, for example, can cause extreme combinations if correlations are not employed. The same is true for all multiplicative components of a PA model. Correlation structures need to be brought into PA, and a DA structure would make it clear for which parameters this is necessary.

Otherwise, mis-specification of correlations can result in model results that are unrealistic given the physical processes represented in the model.

Probabilistic modeling generates probability distributions for endpoint measures that lend themselves to uncertainty analysis, sensitivity analysis, and value of information analysis. Under a DA approach these three types of analyses are tightly coupled and provide a powerful aid to decision making. It allows modelers, stakeholders, and decision makers to see what is important in determining results such as dose to future populations, and therefore provides a basis for guiding further work to refine the modeling under a PA maintenance program. Information collection is prioritized based on the optimal trade-off between resource expenditure and uncertainty reduction in value. As each iteration of data and information collection and modeling reduces uncertainty, it follows that defensibility, transparency and confidence in the model are enhanced. Each iteration provides the decision maker with a more robust basis for decisions and a basis for adaptive management of the site into the future. This is not possible without taking a DA approach. It might be possible to address individual pieces in an *ad hoc* way, but proper model evaluation using these tools is possible only if the system is modeled following a DA approach from identification of decision objectives and options through model specification using probability distributions, costs and value judgments.

Overall, the proposed DA approach is open, transparent and defensible. These seem like basic requirements for modeling any decision problem. Although the model results provides quantification for the decision, the modeling performed is far more important for providing insights into a complex system of uncertainty, value judgments, decision objectives and decision options. The learning process that is inherent in Bayesian implementation of the DA approach to problem solving requires model structuring and model specification that characterizes uncertainty. Probabilistic modeling has become more commonplace in PA, but there are still examples of deterministic or hybrid approaches. The next section provides some further perspectives on realism versus conservatism, and probabilistic versus deterministic modeling.

Human Exposure Scenarios

Another issue that needs to be addressed in the proposed progression to a DA approach to PA is modeling the human environment. Both DOE [2] and NRC [3] specify assessment endpoints for a radiological PA that relate to individual radiation dose, rather than to cancer risk. There are good arguments for suggesting that radiological performance metrics should instead be expressed in the language of risk, as supported by the National Academies in *Risk and Decisions* [9]. The EPA, for example, generally supports evaluating radiological health impacts from environmental contamination as excess cancer risk rather than dose [10]. Radiation dose is a measure of the amount of energy deposited in body tissues, but in practice the dose coefficients published by DOE, EPA, ICRP and other entities incorporate factors that account for the relative biological effectiveness of different types of radiation and the relative sensitivity of different bodily tissues to ionizing radiation. The primary benefits to using cancer risk directly as a performance metric, rather than the proxy of effective dose, are in transparency to stakeholders and the ability to integrate other risks besides radiological exposures in risk management. Most obviously, this includes risks related to chemical exposures in mixed waste disposal facilities. More broadly, if the radiological community were to adopt risk as a common performance metric, PA decisions could then be aligned with other similar work in the realms of hazardous waste management, and any number of other disciplines concerned with risk. That would help to rank radiological risk with other risks in society at large, offering perspective to stakeholders, and leveling the playing field of radioactive waste management. Further, in some cases, additional performance metrics are imposed on PA regarding the behavior of radionuclides in the environment, without direct reference to radiological dose or cancer risk. Examples include concentrations in groundwater or other drinking water sources, and the flux of radon from the ground surface above a disposal site. These radionuclide concentrations and fluxes, however, are ultimately related to cancer risk, since they are developed using analyses that assume certain behaviors and land uses (exposure assessment) and physiological responses in hypothetical human populations (biological effects of radiation). In effect, these proxy performance metrics are also related to cancer risk, and it would be preferable to acknowledge that in the PA modeling effort.

In section 10 CFR 61.41, NRC requires protection of "any member of the public" [3], though the DOE Order refers to protecting "representative future members of the public" and "reference adults" [2]. If the NRC language to be accepted at face value, then this implies that the most vulnerable members of the public should be protected. This would include children, for example, who generally incur higher risks from exposure to radionuclides in the environment than do adults, due to both behavioral and physiological differences.

DOE [2] currently requires the use of DCFs for reference adults, but this is simply an artifact of the lack of a compendium of age-specific DCFs published when Order 435.1 was issued. More recently, ICRP has published age-dependent DCFs in a series of reports. An overall compilation of ingestion and inhalation age-specific DCFs is collected most recently in ICRP Publication 119 [11]. Age-specific exposure information, needed to maintain consistency in the age-dependent dose calculations, is most conveniently available for many exposure pathways in EPA's *Exposure Factors Handbook* [12].

PA models can readily be constructed to consider a variety of ages of the public, just as they can consider a variety of receptor behaviors that might be expected at a given site. For example, a residence at a site may well house infants and children who grow into adults, but a population of well drillers would not include children. Because differences in exposure intensity and physiological response (effective dose or cancer risk) can be easily accommodated in modern PA models, age-specific dosimetry and age-specific exposure information is recommended when performing PA.

If the waste disposal system is considered holistically, it will include the migration of radionuclides from the disposed waste forms into the surrounding environment, their distribution within environmental media to which human receptors could be exposed, and the expected health effects that result from these exposures. However, it might be reasonable in a DA process for PA for the stakeholders to suggest that an ecological risk assessment should be included in the site performance evaluation. A common benchmark for terrestrial animals, based on DOE guidance [13] is 1 mGy (0.1 rad) per day, for which the biologically-effective human equivalent is 1 mSv (100 mrem) per day for external radiation and 50 μSv (5 mrem) per day for alpha radiation (assuming a radiation weighting factor of 20 for alpha [14]). These levels are far in excess of human radiation dose-based standards such as NRC's 0.25-mSv (25-mrem) per yr) dose limit for protection of the public in 10 CFR Part 61, equivalent to 0.68 μSv (0.068 mrem) per day. However, ecological receptors may have much higher levels of exposure than humans if a site-specific exposure scenario indicates only sporadic or highly unlikely future human exposures, and/or if the home range of target ecological receptors is small. Whether an assessment that ensures protection of human health impacts provides adequate protection of ecological receptors is therefore dependent on the characteristics of the human and ecological conceptual models. While such ecological risks are sometimes a concern in the hazardous waste regulatory community, they have not yet caught the attention of the radioactive waste community, so are not considered further in this paper. It is likely that ecological risk will play a larger role in the future if a focus on sustainability in decision-making continues to gain momentum, especially as this relates to impacts on future generations. Nevertheless, the concepts of PA developed here can readily be extended to encompass ecological risk assessment, should that become an interest in the future.

Protection of Future Generations

The time frame in which performance of a radioactive waste disposal site should be evaluated is an issue that has been argued for many years. The DA approach would abandon the notion of time frames of compliance or performance, and, instead, would allow the stakeholders to express their preferences concerning time frames. This would allow the stakeholders, both local and national, to be explicit about inter- and intra-generational equity and the uncertainties involved on a site-specific basis. Local preferences might be different from national preferences, and both should be considered. A concept that has proven useful for consideration is that of the "reasonably foreseeable future", which arguably is intended to represent a time frame for which it is reasonable to project current conditions and knowledge of society, and for which it is reasonable to evaluate risk or dose. Regarding the reasonably foreseeable future, ICRP 81 [15] indicates that dose and risk as measures of health detriment should not be measured beyond a few hundred years; i.e., that they lose meaning in that sort of time frame.

However, in a DA structure the long-term effects of radioactive waste disposal could be considered. The structure is capable of addressing all competing decision objectives of interest in an objectives hierarchy. This can include risk (dose) for receptors in the reasonably foreseeable future, and other types of impacts to the system in a longer time frame (e.g., climate changeor tectonic effects). A DA approach allows the stakeholders to describe their values, which might include the need for long-term protection of the environment, without specific concern about human health.

The current approach to PA includes a compliance period, defined in regulation, corresponding to what amounts to a discount factor of zero through the compliance period, followed by complete discounting thereafter. This is inconsistent with the way in which humans generally act, which involves trade-offs between current and potential future benefits and risks. The willingness to bear costs today to protect future populations may not be constant with regard to how far into the future the effects may be incurred. However, this has not been fully studied in general [16], and especially not with regard to radioactive waste disposal. A DA approach would allow stakeholders to be explicit about their values concerning current and future generations. A proper economic analysis can be set up that protects the near term receptor populations and provides for future generations by investing in that future (setting aside a trust fund for example, or investing in some other socially beneficial infrastructure). Alternatively, stakeholders can express their views that future generations should be protected by disposal in ways that protect future generations. The point is that the model should be driven by stakeholders, which would bring transparency to the process, so that the drivers for decision making are transparent and defensible.

Discount factors include a societal time preference component as well as an economic time preference component. A compliance period includes an implicit societal discount rate that should be made explicit and examined carefully by stakeholders. Discounting functions can take a wide variety of forms to reflect this type of societal preference, which can also be used to model the environmental and ecological sustainability of PA decisions. The key is to make explicit and transparent value judgments that have historically been hidden in the PA process (i.e., the compliance period).

A time frame of hundreds or thousands of years based on the concept of "the reasonably foreseeable future" also aligns with time frames that might be suggested by considering economic and sociologic arguments that address issues of intra- and inter-generational equity. Although economic factors can be challenging to address, continued research in this area is providing more insight on how best to incorporate economic arguments into important long-term issues. Discount factors play a large role in this type of economic analysis, but discounting should not be misconstrued as lack of concern about the long term future. This can be accompanied by investing the money now to address the problem in the future. A discount rate might be specified by local regulators and stakeholders, but the policy implications should be clearly understood. For these reasons, guidance is needed for bringing economic analysis into the waste disposal decision-making process, which can be tied in a regulatory context to the principles of ALARA. It is critically important to address these issues on a site-specific basis, since the economic views of different stakeholder groups should be expected to vary.

Regulatory Consistency Regarding Risk

Regulations that guide PA development should not specify any particular numbers besides the maximum allowable risk to persons, naturally discounted into the future. There is an opportunity to align allowable risk with, for example, the EPA's focus on excess cancer risk for individuals, which may be a more sensible metric than dose. This would allow all risks to be folded into a population risk assessment in order to fully evaluate site performance. For example, many heavy metals associated with radiological wastes, such as uranium and lead, have toxicity risks that can be more important to public health than the radiological risks.

RESULTS AND CONCLUSIONS

The proposed DA approach is consistent with the scientific method. The idea is to build appropriate DA models, including the science-based probabilistic PA models based on the best understanding of the problem and the uncertainties in that understanding, and the critical issues of societal values including intra- and inter-generational equity. The traditional approach to PA, as envisioned in current regulations, is highly conservative, which makes disposal options difficult to identify. It is not possible to defend or understand decisions that are made from conservative models. This information from conservative models is biased and the effects are never very clear. Consequently, conservative modeling does not support development of preference structures, because it is difficult for stakeholders to understand and rank events and options. Instead, DA modeling is aimed at “realistic” modeling (although there must be recognition that “all models are wrong, but some are useful,” to quote George Box). This does not mean that conservative decisions cannot be made; quite the contrary. What it means is that the decision process can be properly explained and communicated, stakeholders can engage in meaningful ways, and decisions are well founded and understood. The point is to understand the risks and manage them. It is not possible to understand risks based on a process that is built with “conservatism on top of conservatism on top of conservatism”. Risk-based decisions are then based on realistic models while characterizing uncertainty, from which decisions can be made and defended, even if the decisions made are conservative.

The traditional science-based PA is still a necessary part of this DA structure, but might not involve detailed modeling for each aspect. Instead the DA approach requires building models that are “as simple as possible and no simpler”. Model evaluation determines where resources should be spent on refining the models. This type of modeling is built from the top down, from the decision perspective, rather than from the bottom up, or from merely the hydrogeological modeling perspective. Some sites might need detailed hydrogeologic models, for example, but some do not, and this approach will help sort through the modeling priorities. A summary of important PA steps is provided in Table I, with a comparison between the traditional approach to PA and this proposed DA approach. There are many crossovers and similarities, but the focus is different.

Table I. Aspects of traditional and innovative performance assessment practice

	traditional approach	**recommended approach**
scoping	*ad hoc*, depending on developers' expertise; consideration of FEPs related to contaminant transport; leads to a conservative CSM	a more rigorous FEPSs process, including human exposure scenarios, leading to perhaps several plausible CSMs
modeling	a collection of specialized, linked process models, often overly detailed	an integrated model, incorporating system-level models of appropriate detail
realism *vs* conservatism	biased towards presumed conservatism, with compounded conservatism	unbiased modeling approaches and inputs, striving toward realism; conservatism to be applied only to the model results
uncertainty and probabilistic modeling	uncertainty incorporated by choosing presumed worst case values and methods	uncertainty incorporated by using unbiased methods and stochastic input parameters
protection of future generations	future generations are given the same weight as current generations	examine alternative means of addressing future risks, costs, and benefits
decision analysis	decisions based on worst case models, resulting in compounded conservatism	decisions based on modeled uncertainty, applying conservatism only to the results

If, as a society, there is a belief that the costs and benefits of the use of radioactivity need to be evaluated, and that legacy waste needs to be safely disposed rather than indefinitely stored above ground, then an approach is needed that better supports maximizing societal benefits for current and future generations. Optimal decisions can be made for disposal, closure and long-term monitoring and maintenance. Insights can be gained into why certain decisions might be made, and the decision model more appropriately reflects what is known and what is not known in a typical PA dose model. Stakeholders drive the preference structures and value judgments, and economic factors are modeled effectively. In this way, conservatism can be applied to the decision options, but not to the model assumptions and inputs, and hence, a more thoughtful risk-informed decision process can be followed. This DA approach can be invoked now through ALARA.

All of the relevant site-specific factors should be included in a comprehensive DA aimed at optimizing the use of a disposal facility. All sites should be evaluated with the same process of using probabilistic risk assessment and ALARA in a DA context that includes stakeholder values and judgments to optimize radioactive waste disposal decisions. This is not intended at all to pre-suppose any decisions. This approach instead provides a structure for a risk-informed decision process. Depending on the results, the long-term consequences of major perturbations to the system, and preferences, costs and value judgments of the stakeholders; optimal decisions can be better supported through this approach. This approach is far more transparent and defensible for decision-making, and provides a framework for gaining insights into the important factors.

However, the process can be expanded beyond the evaluation of specific waste disposal sites to comparison of sites when considering disposal of a particular waste stream, and more generally to better understand the risk management options and consequences of addressing legacy waste and nuclear industries including weapons, energy, medicine, etc. This approach is not new. It is used in a wide range of risk management contexts including environmental risk management problems, and can be brought into PA so that more defensible and transparent decisions are made, and so that the explanations for the decisions made become clearer. This is far better for effective communication of a complex problem such as radioactive waste disposal, and is absolutely necessary for effective decision making.

REFERENCES

1. EPA, 40 CFR 191, 2005, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*, Code of Federal Regulations, as amended, U.S. Environmental Protection Agency
2. DOE, 1999, *Radioactive Waste Management*, DOE Order 435.1-1, U.S. Department of Energy (also see the Manual, DOE M 435.1-1)
3. NRC, 10 CFR 61, *Licensing Requirements for Land Disposal of Radioactive Waste*, Code of Federal Regulations, as amended, U.S. Nuclear Regulatory Commission
4. Gregory, R., L. Failing, M. Harstone, G. Long, T. McDaniels, and D. Ohlson, 2012, *Structured Decision Making: A Practical Guide to Environmental Management Choices*, Wiley
5. Keeney, R., 1992, *Value-focused Thinking*, Harvard University Press
6. Clemen R. and T. Reilly, 2001, *Making Hard Decisions*, Duxbury Press, Pacific Grove, CA
7. Morgan G. and M. Henrion, 1990, *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Decisions*, Cambridge University Press
8. Kocher D.C., A.I. Apostoaei, and F.O. Hoffman, 2005, *Radiation effectiveness factors for use in calculating probability of causation of radiogenic cancers*. Health Physics 89(1): 3-32
9. National Research Council, 2005, *Risk and Decisions*, National Academies Press, Washington, DC
10. EPA, 1997, *Establishment of Cleanup Levels for CERCLA Sites with Radioactive Contamination*, Memorandum from S. D. Luftig, Director Office of Emergency and Remedial Response, and L. Weinstock, Acting Director Office of Radiation and Indoor Air, U.S. Environmental Protection Agency, Washington, DC
11. ICRP, 2012, *Compendium of Dose Coefficients based in ICRP Publication 60*, International Commission on Radiological Protection Publication No. 119, Ann. ICRP 41(Suppl.)
12. EPA, 2011, *Exposure Factors Handbook: 2011 Edition*, EPA/600/R-090/052F, National Center for Environmental Assessment, Office of Research and Development
13. DOE, 2002, *A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota*, DOE-STD-1153-2002, U.S. Department of Energy, Washington, DC
14. ICRP, 1991, *Recommendations of the International Commission on Radiological Protection*; International Commission on Radiological Protection Publication No. 60. Ann. ICRP 21(1–3)
15. ICRP, 2000, *Radiation Protection Recommendations as Applied to the Disposal of Long-lived Solid Radioactive Waste*, International Commission on Radiological Protection Publication No. 81
16. Robinson, L., and J. Hammitt, 2011, *Behavioral Economics and Regulatory Analysis*. Risk Analysis, Vol 31, No. 9