PERFORMANCE ASSESSMENT FOR ENVIRONMENTAL DECISION MAKING

D.R. Anderson, Ph.D.
M.E. Fewell, Ph.D.
L.S. Gomez, Ph.D.
M.G. Marietta, Ph.D.
P.N. Swift, Ph.D.
K.M. Trauth, Ph.D., P.E.
P. Vaughn, Ph.D.
Sandia National Laboratories
Albuquerque, NM 87185-1328

R.J. MacKinnon, Ph.D.
Applied Physics Inc.
Albuquerque, NM 87110

ABSTRACT

The Waste Isolation Pilot Plant (WIPP) Performance Assessment Departments at Sandia National Laboratories have, over the last twenty (20) years, developed unique, internationally-recognized performance and risk assessment methods to assess options for the safe disposal and remediation of radioactive and non-radioactive hazardous waste/contamination in geohydrologic systems. While these methods were originally developed for the disposal of nuclear waste, ongoing improvements and extensions make them equally applicable to a variety of environmental problems such as those associated with the remediation of EPA-designated Superfund sites and the more generic Brownfield sites (industrial sites whose future use is restricted because of real or perceived contamination). The Sandia methodology has been successfully applied in terrestrial and in marine environments; applications include the WIPP and the Subseabed Disposal Project. The methodology enables prioritization of site characterization information and remediation options so that maximum benefit can be achieved from available resources while meeting site performance goals.

The core of Sandia's capability is a probabilistic approach for assessment of health risks posed by contaminant mixtures and their potential migration. Sandia has advanced this capability by quantifying uncertainty in site characterization and in future events for the assessment. The evaluation of the impacts of these uncertainties on risk or regulatory compliance provides the foundation for choosing cost-effective remediation approaches while allowing the site owner to prioritize the value of additional data and site characterization information. Sandia's methodology combines the accuracy of science-based mathematical modeling with a decision-oriented evaluation process. This approach goes beyond the traditional risk and decision analysis methods by evaluating alternatives in a probabilistic fashion that incorporates uncertainty and that is less conservative than many other approaches (e.g., not using "worst case" assumptions), and therefore is more effective for decision making.

The unique Sandia methodology provides the decision-maker with a basis for making, communicating, and defending decisions to stakeholders, such as the public, and governing and regulatory agencies. A thorough system of life cycle quality assurance has been developed and implemented for the codes themselves, for tracking computations, and for the analysis of computational results. The scientific foundations of the methodology and early incorporation of public concerns in the assessment may reduce the possibility and cost of litigation.

DISCLAIMER

BACKGROUND

Risk is usually defined as the product of the probability that an undesirable event will occur (i.e., release of a risk agent such as a chemical substance) and the consequences (i.e., adverse health effects such as cancer) that occur as a result of the undesirable event[1]. Therefore, the assessment of human-health risk posed by a contaminated site must account for the probability that risk agents will be released from their source and result in human exposure, and for the impacts of any such exposure. Outside of a risk-based assessment, decision makers often make the "worst case" assumption that undesirable events such as the release of *in situ* chemicals to the surrounding soil are certain to occur. Human health risks associated with site remediation can be divided into (1) long-term risks posed by contamination if no remedial action is taken, (2) long-term risk associated with residual contamination after remedial action is taken, and (3) short-term risks to on-site and off-site humans posed by the implementation of remedial alternatives. The assessment of human health risks has become the primary incentive for estimating relative dangers of contamination and for establishing the need for remedial action. The advantage of Sandia's total system assessment methodology is that it allows identification of specific factors (design parameters and data) that have the largest overall impact on reducing predicted risks and avoids focusing resources on activities not requiring such attention. Moreover, this approach allows a broad suite of remedial technologies to be evaluated in a consistent manner with respect to long-term health risk, short-term health risk, environmental impact, characterization and remediation costs, duration of remediation, and uncertainty in all of the above factors.

Uncertainty

Uncertainty is almost always a factor in the decision making process. Uncertainty in site assessment and remediation arises from several sources[1,2,3,4]. One type of uncertainty arises from the limited amount of field data that can be gathered at a site, the imprecise knowledge of physical, chemical, and biological processes that control the transport and fate of contaminants, and the lack of knowledge about factors such as exposure frequency and duration. A second and equally important source of uncertainty arises from a lack of engineering and economic data characterizing the performance and cost of remedial technologies under different site conditions and at different physical scales of application. Another important source of uncertainty arises from the inability to accurately predict future human behavior and technological practices at the site. In the past, treatment of uncertainties has been bypassed by introducing "worst case" assumptions into assessments[5]. Regulators and stakeholders, however, are becoming aware that this approach may often result in very conservative assessments (e.g., using "worst case" assumptions) and very high remediation costs with little actual risk-reduction benefit. In addition, defensible "worst case" assumptions cannot always be identified in complex geologic systems. Regulators and stakeholders are also realizing that outputs from simulation models reported as single deterministic values are inadequate and that formal assessments of uncertainties provide better estimates of the margin of safety for meeting regulatory requirements. As a consequence, regulators and stakeholders are beginning to regard the quantification of uncertainty as an indispensable component of site assessments[6].

Performance, Risk, and Decision Analysis

During the last 20 years Sandia has, with the Department of Energy's (DOE's) funding, developed and applied a systems-based approach to hazardous waste site assessment that incorporates performance, risk, and decision analysis (PRDA). The approach assesses the long-term behavior of contaminant mixtures in complex geologic environments. This work began with DOE's subseabed high-level radioactive waste disposal program[7] and continues today with the assessment of long-term performance of the Waste Isolation Pilot Plant (WIPP)[4,8,9,10,11], a deep geologic transuranic waste repository. PRDA is specifically designed to predict system performance, while incorporating uncertainty and overcoming many of the shortcomings associated with standard risk and performance assessment methodology. These shortcomings include using deterministic analyses that are conservative and often use "worst case" assumptions, paired with decision making that is intuitive or experience-based. The tools and expertise developed to implement PRDA include the following:

1) A proven probabilistic system assessment methodology capable of integrating diverse physical, chemical, and biological processes for predicting and optimizing geologic system response to the presence of complex contaminant mixtures. This capability provides the framework for integrating risk assessment, site characterization, laboratory programs, remedial technology selection and implementation, and quantifying the impact of parameter and model uncertainty on system or process response.

2) A proven set of numerical source-term, flow, and transport models that interface with each other and

are managed through Sandia's system assessment management software. These computational models predict contaminant release, multiphase fluid flow, and multispecies contaminant transport through porous or fractured media in one, two, and three dimensions, given a set of operating assumptions.

3) A data management and integration system capable of organizing and making available to analysts a wide range of diverse information used for the computational models of multidisciplinary projects such as site assessment and remediation. This system also addresses important quality assurance issues such as traceability, reproducibility, and providing software verification documentation.

4) A flexible and modular software system that allows both the incorporation of new advances in software technology and multiple alternative computational models. The latter feature is particularly beneficial for sites where computational models have been developed to meet their unique, site-specific requirements, including stakeholder concerns. Models which have been used by site owners/operators can also be incorporated into the Sandia modeling structure.

5) A method for analyzing life-cycle costs to help determine the most cost-effective site-specific characterization and/or remedial alternative. The PRDA methodology is flexible enough to employ calculations or information gathered from technology vendors. Such information allows comparison of alternatives based on cost and schedule along with performance and uncertainty in performance.

6) A method for collecting information from the public regarding perceptions of risk and preferences for dealing with the risk.

7) Decision analysis of alternative remediation technologies and site characterization activities in terms of their predicted contribution to meeting performance objectives. These methods also allow examination of trade-offs between various attributes of remedial options (including health risks, remediation cost, and remediation duration) and site-specific remediation goals.

8) A state-of-the-art computation and networking facility dedicated to geologic systems assessment. This system includes the necessary hardware required for running computationally-intensive sets of probabilistic assessment and remediation design calculations and managing and storing large amounts of data, as well as providing the convenience of "PC"-based Internet access.

Probabilistic Approach

At the core of Sandia's PRDA methodology is a probabilistic approach for assessing health risks posed by contaminant mixtures in marine and/or terrestrial geologic environments. This approach uses a linked system of deterministic consequence models (coupled source-term, multiphase flow, and transport models) to represent the contaminated site and associated geologic system, and a Monte Carlo technique that relies on multiple simulations using sampled values for selected input parameters to propagate uncertainty through to the calculation of system performance measures. A full analysis includes selecting imprecisely known parameters to be sampled, constructing distribution functions for each of these parameters (incorporating available data and subjective information to capture the uncertainty), generating a sample set by selecting a parameter value from each distribution function, and calculating consequences for the sample set. This procedure is repeated many times to produce distributions of model outcomes (consequences) that represent the spectrum of potential system consequences. Sandia's performance assessment methodology uses a stratified sampling technique called Latin hypercube sampling (LHS) to determine the input sample sets[12]. This procedure ensures full coverage of the range of each sampled variable and is often a more efficient technique than simple random sampling in that fewer sample elements are required for a Monte Carlo analysis.

The construction of distributions for uncertain parameters is an important element of any type of Monte Carlo analysis and Sandia has developed several techniques for this purpose[13]. These techniques fall into three classes: (1) direct use of data to construct an empirical distribution function; (2) finding the analytic distribution that best fits the data (e.g., through the use of the Kolmogorov-Smirnov test or the chi-squared test), and (3) Bayesian techniques that combine available data and expert judgment to form prior and distribution functions (before and after additional information is gathered). The third class includes all subjective procedures that rely entirely upon expert judgment to assign a shape to the distribution. The amount of subjective judgment required by these techniques increases from class 1 to 3. Sandia has found that the "best" technique to be used in a particular situation depends strongly upon the kinds and amounts of empirical data and subjective information that are available concerning the parameter.

Monte Carlo analysis can be computationally intensive, particularly when the site being assessed is represented by realistic, multidimensional consequence models. To alleviate this drawback, Sandia has developed a considerable amount of expertise and insight into the process of tailoring and streamlining Monte Carlo calculations for specific applications. For example, considerations in planning calculations typically include (1) identification of cases for which different calculations are independent and hence can be performed separately, (2) elimination of calculations for which results can be reasonably anticipated on the basis of prior analysis and experience, (3) decomposition of calculations so that a single computationally-demanding calculation can provide input to a number of less demanding calculations, and (4) identification of cases where the results of a calculation can be scaled up or down and used in place of multiple calculations.

Computational results from a probabilistic assessment include time-dependent releases of contaminants to various locations in the environment with the associated probabilities, and doses to humans at various times and locations with the associated probabilities. These releases and doses can be paired with the associated costs of remediation. These outcomes can be represented graphically in the form of cumulative distribution functions (CDFs) that plot the probability of occurrence against outcome. In addition, selected statistical measures such as the median, tenth, and ninetieth quantiles of the performance measures are obtained. These measures can be used to summarize the uncertainty in the margin of safety and confidence levels of risk predictions and system performance with and without remediation. To facilitate the understanding of both computational results and parameters, Sandia has developed an interactive, graphical tool called Ask PA! that allows interested parties to access the input information and results from probabilistic analyses.

Sensitivity Analysis

In addition to producing the overall probabilistic results of a risk assessment, another important component of Sandia's PRDA methodology is a sensitivity analysis. A sensitivity analysis is used to identify the relative importance of input parameters to the predicted behavior of a system. If a parameter has a significant effect on the predicted response of the system and the associated uncertainty is unacceptable, additional data are needed to reduce the uncertainty and should be included in site characterization and/or laboratory activities. However, if system response is insensitive to the parameter, or if the level of uncertainty is acceptable, the parameter can be excluded from further testing programs.

Life Cycle Costs

Another component of Sandia's total system assessment methodology is the method for analyzing life cycle costs to help determine the most cost-effective site characterization activities and options for site remediation. In order to save computational time and to utilize state-of-the-art characterization and remediation technologies, the methodology is flexible enough to incorporate information from a variety of sources. One category of sources is technology vendors who can provide cost, duration, and effectiveness information for remediation options based on day-in and day-out experience with the technology. Estimates of the contaminants remaining after remediation become inputs to the risk assessment whose movement, etc., is then modeled to predict performance measures. This approach allows decision makers to compare alternatives on the basis of cost, schedule, performance, and key contributors to the uncertainty in the forecasted performance.

Decision-Making Process

The decision-making process is another important component of Sandia's PRDA methodology that provides a structured approach to evaluating remedial alternatives in terms of their predicted contribution to meeting performance objectives (e.g., permissible risk, maximum contaminant levels, etc.) and costs and schedule. Results of probabilistic cost and remediation-duration analyses feed into the decision-making process to permit determination of the most cost-effective remedial option. Decision analysis is used to develop this information and present it in a form that aids decision making and allows examination of trade-offs among various attributes of remedial options (including cost, duration, and types and amounts of wastes produced) and site-specific remediation goals (including short-term and long-term risks, doses, concentrations, and levels of uncertainty).

IMPLEMENTATION OF PRDA

Sandia's PRDA for addressing the decision points for contaminated sites integrates five major phases,

1) project planning with public involvement,
2) remedial alternatives evaluation,
3) risk assessment,
4) remediation technology selection, and
5) assessments during remediation,

into a comprehensive decision-making strategy. This strategy is discussed in the following paragraphs. It should be emphasized that although the phases in the PRDA process appear to be distinct, in practice they, and the activities conducted within them, are strongly interrelated. In addition, PRDA is a flexible process that can be tailored to site-specific needs and should not be viewed as a rigid process that is conducted identically at every site.

Phase 1: Project Planning with Public Involvement

The primary objectives of Phase 1 are to determine if site characterization and/or remedial action appear to be warranted, and if so, to develop an initial site characterization plan that will collect necessary data and information. This phase consists of the following tasks: (1) gather existing data and information; (2) identify and analyze applicable regulations to determine mandatory limits on risk, dose, or other performance measures and to determine any regulatory constraints on how a site is to be evaluated; (3) query the public through such venues as public meetings or focus groups to determine the nature of any specific concerns they have about the contaminated site and the risks associated with it, to assess preferences for particular remedial alternatives, and to discover the reasons for the preferences; (4) develop an initial conceptual model of the site, incorporating existing data that is both useful and of high enough quality and incorporating any regulatory constraints; (5) conduct a screening integrated risk assessment (IRA) with sensitivity analysis. (The integrated risk assessment with sensitivity analysis is a special capability of the Sandia methodology that can be performed as various stages of a project, and is discussed in greater detail later in the paper.); (6) translate public preferences into potential impacts to determine if incorporating them would require stricter measures than the regulatory requirements; and (7) compare the calculation results with the regulatory limits to determine if remedial action appears warranted. There may also be cases in which regulatory limits are expected to be met, but the uncertainties may be too great for the results to be accepted by a regulatory agency. In these cases, additional site characterization may be necessary, without any remedial action. There may also be cases where regulatory limits are expected to be met, but where there may be social, religious, cultural, and political issues that could influence the need for action at a site and the level of chemicals that can remain on site[14]. Thus, the need to assess public perceptions.

Phase 2: Remedial Alternatives Evaluation

The major purpose of Phase 2 is to develop a list of viable remedial alternatives for detailed evaluation in Phase 3. Specific steps that are undertaken are: (1) create a list of potential site remedial alternatives (technologies or processes); (2) identify any special input data required to evaluate the alternative (e.g., impact of a pump, treat and replace alternative on the hydraulic conductivity of the formation); (3) for each of several levels of clean up by an alternative (e.g., removal of 10%, 50%, and 90% of the contamination in a given area), develop an analysis of life cycle costs and treatment process durations (including for any additional data collection necessary), along with an assessment of the maturity of the technology and the ability to achieve the specified clean up on time and within budget; (4) establish screening criteria for the remedial alternatives (e.g., costs, durations, data requirements, types of wastes generated, and amounts of waste generated); and (5) screen potential remedial alternatives for further consideration.

Note that in some cases, results of a screening risk assessment may indicate that remedial action is not required. In such cases, it may be preferable to bypass Phase 2 altogether and avoid the costs associated with screening remedial alternatives. If it is ultimately determined, however, that remedial action is required, it may be necessary to return to Phase 2 from Phase 3. Bypassing Phase 2 may be prudent in simple contamination settings only and consideration of potential remedial alternatives, at least on a cursory level, is recommended in case it is ultimately determined that remedial action is necessary. This latter approach will help avoid the pitfalls of focusing the calculations and site characterization activities solely on the baseline probabilistic risk assessment and neglecting the needs of remedial alternative evaluation.

Phase 3: Risk Assessment

The objective of Phase 3 is to create a useful set of calculational results by which decision makers can compare the costs and benefits of various remedial alternatives that meet regulatory requirements. The specific tasks in Phase 3 include: (1) formulate the Risk Assessment Computation Plan for the "screened-in" remedial alternatives; (2) assess whether the available data and information are sufficient to evaluate the remedial alternatives or if a site owner must collect additional information prior to the assessments; (3) conduct integrated risk assessments; (4) assemble the calculational results of the IRA (in both words and with a graphical representation) so that the regulatory limit(s) (e.g., risk, dose, concentration) is/are associated with the cost, duration, probability of success, and level of uncertainty; (5) assess whether any of the remedial alternatives evaluated provide a sufficient reduction in the source term for the site to meet regulatory limits (not meeting regulatory limits would require considering other technologies or combinations of technologies and a return to Phase 2); and (6) assess the acceptability of the level of uncertainty associated with the baseline and/or the remedial alternatives (an unacceptably high level of uncertainty would indicate that additional data and information would need to be collected and the IRA repeated and reassessed).

In general, the level of acceptable uncertainty depends on how close the predicted health risk or other established performance measures approach the regulatory limit. For contaminated sites where the predicted risk is considerably lower than regulatory limits, larger uncertainty is acceptable and remediation is not required. For systems having predicted risk close to or above the regulatory limit, the uncertainty in parameter values will need to be reduced by additional site characterization and/or by the implementation of additional or different remediation activities (i.e., allowing the narrowing of the range of values from which the sample used in the Monte Carlo analysis is drawn and/or lowering the range of the source term).

The Risk Assessment Computation Plan ensures that the overall structure of the risk calculations is carefully planned to avoid unnecessary calculations and minimize computation costs. In addition, the Plan would include the necessary changes to the source term and to model configurations dictated by the implementation of a remedial alternative and any associated changes to the conceptual model of the site after remediation (e.g., changes in hydraulic conductivity). The Plan may be modified in an iterative manner if additional calculations are deemed appropriate during the decision-making process.

Due to the expense of performing Monte Carlo calculations, the overall structure of the risk assessment analysis must be carefully planned in Phase 3 so that the baseline and remedial alternative risk assessments are cost-effective and technically defensible. Sandia has developed a considerable amount of expertise and insight into the process of tailoring and streamlining Monte Carlo calculations for specific applications. In many practical cases process linearity can be invoked in the mathematical representation of the dominant release and transport processes. This simplification enables a linearized representation of the groundwater pathway source term. In this case, results of a groundwater pathway consequence analysis may then be scaled up or down depending on the estimated range of actual concentrations at the source and the effectiveness of the remedial alternative. As a result, a single calculation can be extended to several remedial alternatives.

In Phase 3, IRAs are conducted for the baseline case (no action alternative) if needed and each "screened-in" remedial alternative. During this phase, potential impacts on human health and the environment are quantified for each level of cleanup that may be associated with a remedial alternative. This information provides input for decision making and the selection of the most appropriate remedial alternative in Phase 4.

Phase 4: Remediation Technology Selection

In Phase 4, each remedial alternative is assessed against an array of evaluation criteria. This decision analysis process is conducted with an information management system that links applicable regulatory requirements and stakeholder preferences with costs, durations, probabilities of success, and levels of uncertainty to identify key tradeoffs with each alternative. Sandia is currently developing decision-aiding tools that can be used in an interactive setting with regulators and stakeholders to communicate (1) the nature of the impacts of the evaluated alternatives, and (2) the risk-cost-duration implications of these alternatives, so that a remedial alternative can be selected.

Phase 5: Assessments During Remediation

In the final phase of the total systems-based approach, integrated risk assessments are performed in support of site remediation activities. In this phase, risk assessments are used to (1) assess whether previous conclusions about the site itself or the effectiveness of the selected remedial alternative were correct, and (2) provide interim guidance for potential mid-course corrections during remediation to ensure that the regulatory and stakeholder requirements will be met. In general, risk assessments are conducted in the probabilistic framework and use the previously developed parameter distributions, modified as necessary to incorporate real world conditions encountered in the field and the actual effectiveness of the selected remedial alternative.

SANDIA'S INTEGRATED RISK ASSESSMENT PROCESS

As described in the foregoing discussion, Sandia's PRDA methodology incorporates an integrated risk assessment (IRA) process. This process can be implemented at several points during site evaluation and remediation decision making, and is used to conduct the screening risk assessment and the baseline and remedial alternative risk assessments. Important steps of the process and how they are interrelated are summarized briefly below.

Step 1: Evaluate Data

Available data and information are evaluated for their quality and potential utility in understanding the site and evaluating remedial alternatives.

Step 2: Refine Conceptual Models

Information from the previous step is used to form assumptions and to develop qualitative descriptions of system behavior (both the system as it exists now, and the system as might be affected by the implementation of a remedial alternative). Contaminants of concern, potential chemical fate and transport pathways, exposure routes, exposure scenarios, and plausible future events are identified. Traceable methods are employed to record input from stakeholders and technical and other experts. A key component of this step is the list of assumptions regarding dimensionality of the system, important physical and chemical processes, and initial and boundary conditions. In Phase 1 of the total-system-assessment process, the site conceptual model is based on existing information and expert judgment. This model is conservative in the sense that sources, pathways, and receptors should be deleted only if they are clearly not applicable to the site. In Phase 3, remedial alternative conceptual models are developed that incorporate any changes to the system associated with the operation of the process or the waste treatment end products. If it is deemed useful to collect additional data before the evaluation of remedial alternatives, the site conceptual model could be refined and made more specific based on the new information. Refinement could be accomplished by eliminating receptors, routes of exposure, and potential sources that are not deemed to be credible or important.

Step 3: Develop Parameter Distributions

Based on information gathered in the previous steps, uncertain parameters are selected and parameter probability distributions are defined using methods described previously. The initial goal in this step is to define uncertain parameters by retaining broad ranges of values within the limits of available information. If additional data and information are collected for use in subsequent iterations, ranges of parameter distributions could be refined.

Step 4: Estimation of Probabilities

In this step, probabilities are assigned to exposure scenarios and future events identified in Step 2. Assignment of probabilities always begins with examining regulatory guidance and requirements to determine any assumptions or procedures that must be a part of the process. These probabilities are used as a part of estimating risk, which is usually defined as the product of the consequence (due to an exposure scenario or future event) and the probability of that consequence occurring. Note that outside of a risk-based assessment, it is often assumed that primary exposure scenarios and future events have a unit probability of occurrence. Sandia's approach eliminates this "worst case" conservatism.

Step 5: Construct System Model

Mathematical representations of the conceptual models are constructed, coded into predictive computer models, and linked together. Predictive codes are codes that model geophysical, geochemical, and biological processes. Test calculations are carried out to ensure correct interfaces between models.

Step 6: Consequence Modeling

In this step, parameter uncertainty is propagated through the predictive codes using Monte Carlo simulations so that distributions of doses, maximum contaminant levels, and risks are obtained.

Step 7: Sensitivity Analysis

Sensitivity analysis is performed on the results of the consequence analysis to evaluate which processes, parameters, and combinations of parameters are most significant in influencing the predicted performance of the system. The primary goals of this step are to identify and rank, in order of importance, data and assumptions that influence predicted results. This information is used to prioritize site characterization activities and make model improvements, and, most importantly, model simplifications.

SOFTWARE SYSTEM

Sandia's PRDA is implemented by a software system comprised of a suite of scientific software modules, a centralized database, and an information management system. The software system is designed to be flexible enough to permit both substitution of alternative software modules and modification of software modules to meet site-specific needs. The software system not only draws upon many software modules in the Sandia Nuclear

Waste Management Center's geologic system assessment library, but also on other software developed in the maintenance of Sandia's core competencies in computational fluid dynamics and heat transfer, chemistry, physics, and nuclear reactor safety and risk analysis. All scientific software modules are divided into three categories, namely, (1) predictive codes (i.e., consequence models), (2) service codes, and (3) statistical analysis codes. Service codes perform routine operations in support of predictive codes such as data transfer, grid generation, and postprocessing. Statistical codes collect, prepare, and perform statistical analyses of the computational results and analyze sensitivities. The centralized database stores the information that defines parameter values for the process models. The information management system allows analysts and interested parties to review, analyze, and understand the large amounts of information produced from probabilistic analyses.

SUMMARY

Assessing hazards at a waste or contamination site in order to evaluate and select an appropriate remediation method generally involves five major phases: (1) project planning with public involvement, (2) remedial alternative evaluation, (3) risk assessment, (4) remedial technology selection, and (5) assessments during remediation. Each of these phases has key activities. *Project planning with public involvement* answers the all-important question of whether site remediation appears necessary, within the context of public perceptions about the risks associated with the site and what should be done about them. *Remedial alternative evaluation* provides a list of viable remedial alternatives for detailed evaluation. *Risk assessment* provides a set of calculational results that can be used to compare the costs and benefits of remedial alternatives that meet regulatory requirements. *Remedial technology selection* is a decision analysis process by which the technology is selected that will best meet site-remediation goals while satisfying stakeholder preferences, and costs and schedule constraints. *Assessments during remediation* provide interim guidance for potential mid-course corrections during remediation.

Sandia National Laboratories stresses a systems-based approach to contaminated site assessment that incorporates performance, risk, and decision analysis (i.e., PRDA). This approach provides the basis for integrating these activities to provide well-structured, technically practicable, and cost-effective alternatives for environmental cleanup. Sandia's PRDA differs from traditional risk analysis by going beyond describing risk and uncertainty to propagating uncertainty through calculations in order to evaluate alternatives for reducing risk, and by associating potential risk reductions with cost and schedule constraints for use in decision making. It also differs from traditional decision analysis in the level of scientific inquiry and modeling that forms the basis for the evaluation of alternative courses of action. Traditional decision analysis is most often applied at a macro level, using simple, lumped-parameter models, with intuition and subjective estimates playing a major in the evaluation. While some subjectivity is unavoidable, Sandia's PRDA is based on a technically-defensible understanding of the system under study that goes well beyond typical decision analysis studies. For complex and contentious issues, this rigorous and defensible approach is essential in developing effective, implementable plans that can achieve meaningful and measurable results. More specifically, the Sandia approach allows site owners and managers to:

1) Establish site-specific remediation goals that are based on a mandated limits to health risks, doses, or environmental concentrations, with consideration of public preferences;
2) Prioritize data needs based on the relative importance of data to the prediction of health risk and the establishment of remediation goals;
3) Evaluate health risks and costs associated with various remedial alternatives;
4) Quantify uncertainties in site characterization, risks, doses, and other performance measures; and
5) Examine trade-offs among various attributes of remedial options (including cost, duration, types and amounts of wastes produced) and site-specific remediation goals (including short-term and long-term risks, doses, concentrations, and levels of uncertainty).

It is also important to stress that Sandia's PRDA approach to site assessment is a flexible process that can be tailored to meet site-specific needs and it is compatible with the United States Environmental Protection Agency's (U.S. EPA's) Risk Assessment Guidance for Superfund (1989)[15].

Sandia is a multipurpose laboratory operated by Sandia Corporation, A Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

REFERENCES

1. Helton, J.C. 1993. "Risk, Uncertainty in Risk, and the EPA Release Limits For Radioactive Waste Disposal," *Nuclear Technology*. SAND91-1255J. Vol. 101, no. 1, 18-39.

2. Labieniec, P.A., D.A. Dzombak, and R.L. Siegrist. 1997. "Evaluation of Uncertainty in a Site-Specific Risk Assessment," *Journal of Environmental Engineering*. Vol. 123, no. 3, 234-243.

3. Boak, D.M., and L. Painton. 1996. "A Probabilistic Approach to Cost and Duration Uncertainties in Environmental Decisions," *SPECTRUM '96, Proceedings of the International Topical Meeting on Nuclear and Hazardous Waste Management, Seattle, WA, August 18-23, 1996*. La Grange Park, IL: American Nuclear Society. Vol. 1, 700-708.

4. Marietta, M.G., S.G. Bertram-Howery, D.R. Anderson, K.F. Brinster, R.V. Guzowski, H. Iuzzolino, and R.P. Rechard. 1989. *Performance Assessment Methodology Demonstration: Methodology Development for Evaluating Compliance With EPA 40 CFR 191, Subpart B, for the Waste Isolation Pilot Plant*. SAND89-2027. Albuquerque, NM: Sandia National Laboratories.

5. Thompson, K.M., and J.D. Graham. 1996. "Going Beyond the Single Number: Using Probabilistic Risk Assessment to Improve Risk Management," *Human and Ecological Risk Assessment*. Vol. 2, no. 4, 1008-1034.

6. U.S. Environmental Protection Agency. 1995. "Monte Carlo Analysis, Recent Actions Point to New EPA Acceptance of Risk Tool, News Analysis," *Risk Policy Report*. February 21, 1995, 31-32.

7. Gomez, L.S., A.A. Yayanos, and D.W. Jackson. 1987. "Subseabed Disposal of High-Level Nuclear Wastes," *Advances in Radiation Biology. Volume 13*. Ed. J.T. Lett. San Diego, CA: Academic Press. 355-402.

8. WIPP Performance Assessment Department. 1992. *Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992. Volume 2: Technical Basis*. SAND92-0700/2. Albuquerque, NM: Sandia National Laboratories.

9. Helton, J.C., D.R. Anderson, B.L. Baker, J.E. Bean, J.W. Berglund, W. Beyeler, R. Blaine, K. Economy, J.W. Garner, S.C. Hora, R.C. Lincoln, M.G. Marietta, F.T. Mendenhall, N.H. Prindle, D.K. Rudeen, J.D. Schreiber, A.W. Shiver, L.N. Smith, P.N. Swift, and P. Vaughn. 1996. *Computational Implementation of a Systems Prioritization Methodology for the Waste Isolation Pilot Plant: A Preliminary Example*. SAND94-3069. Albuquerque, NM: Sandia National Laboratories.

10. Helton, J.C., D.R. Anderson, B.L. Baker, J.E. Bean, J.W. Berglund, W. Beyeler, J.W. Garner, H.J. Iuzzolino, M.G. Marietta, R.P. Rechard, P.J. Roache, D.K. Rudeen, J.D. Schreiber, P.N. Swift, M.S. Tierney, and P. Vaughn. 1995. "Effect of Alternative Conceptual Models in a Preliminary Performance Assessment for the Waste Isolation Pilot Plant," *Nuclear Engineering and Design*. SAND94-2312J. Vol. 154, no. 3, 251-344.

11. U.S. Department of Energy, Carlsbad Area Office. 1996. *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant*. DOE/CAO-1996-2184. Carlsbad, NM: Carlsbad Area Office, U.S. Department of Energy.

12. Iman, R.L., and M.J. Shortencarier. 1984. *A FORTRAN 77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use with Computer Models*. NUREG/CR-3624. SAND83-2365. Albuquerque, NM: Sandia National Laboratories.

13. Tierney, M.S. 1994. "Using Data and Information to Form Distributions of Model Parameters in Stochastic Simulation of Performance of the Waste Isolation Pilot Plant (WIPP)," *Proceedings of the International Conference on Probabilistic Safety Assessment and Management (PSAM) - II, San Diego, CA, March 20-25, 1994*. Eds. G.A. Apostolakis and J.S. Wu. SAND93-1302A. Los Angeles, CA: University of California at Los Angeles. Vol. 2, 051-9 - 051-16.

14. U.S. Department of Energy. 1995. *Environmental Justice Strategy, Executive Order 12898*. Washington, DC: U.S. Department of Energy.

15. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response. 1989. *Risk Assessment Guidance for Superfund, Volume I, Human Health Evaluation Manual (Part A), Interim Final*. EPA/540/1-89/002. Washington, DC: U.S. Environmental Protection Agency.

M98001675

Report Number (14) SAND--97-0723C
CONF-971223--

Publ. Date (11) 199712

Sponsor Code (18) DOE/MA, XF

UC Category (19) UC-900, DOE/ER

DOE