Evolution of USDOE Performance Assessments Over 20 Years – 13597

Linda C. Suttora*, Roger R. Seitz**
* U.S. Department of Energy, Office of Site Restoration, 19901 Germantown Rd, Germantown, MD 20874-1290
** Savannah River National Laboratory, Savannah River Site, Bldg 773-43A, Aiken, SC 29808

ABSTRACT

Performance assessments (PAs) have been used for many years for the analysis of post-closure hazards associated with a radioactive waste disposal facility and to provide a reasonable expectation of the ability of the site and facility design to meet objectives for the protection of members of the public and the environment. The use of PA to support decision-making for LLW disposal facilities has been mandated in United States Department of Energy (USDOE) directives governing radioactive waste management since 1988 (currently DOE Order 435.1, *Radioactive Waste Management*). Prior to that time, PAs were also used in a less formal role.

Over the past 20+ years, the USDOE approach to conduct, review and apply PAs has evolved into an efficient, rigorous and mature process that includes specific requirements for continuous improvement and independent reviews. The PA process has evolved through refinement of a graded and iterative approach designed to help focus efforts on those aspects of the problem expected to have the greatest influence on the decision being made. Many of the evolutionary changes to the PA process are linked to the refinement of the PA maintenance concept that has proven to be an important element of USDOE PA requirements in the context of supporting decision-making for safe disposal of LLW.

The PA maintenance concept represents the evolution of the graded and iterative philosophy and has helped to drive the evolution of PAs from a deterministic compliance calculation into a systematic approach that helps to focus on critical aspects of the disposal system in a manner designed to provide a more informed basis for decision-making throughout the life of a disposal facility (e.g., monitoring, research and testing, waste acceptance criteria, design improvements, data collection, model refinements). A significant evolution in PA modeling has been associated with improved use of uncertainty and sensitivity analysis techniques to support efficient implementation of the graded and iterative approach. Rather than attempt to exactly predict the migration of radionuclides in a disposal unit, the best PAs have evolved into tools that provide a range of results to guide decision-makers in planning the most efficient, cost effective, and safe disposal of radionuclides.

INTRODUCTION

LLW disposal at USDOE facilities is regulated under DOE Manual 435.1-1, *Radioactive Waste Management* [1], which provides performance objectives and requirements that provide for safe and controlled disposal of LLW. In DOE Manual 435.1-1, PAs are required to assess the long-term risk of disposing of radioactive waste in on-site disposal facilities and to support decision-making regarding the waste types, volumes, waste form and containers, and disposal facility design. USDOE conducts mathematical modeling to determine whether there is a reasonable expectation that the releases from the disposal facility will not result in exceeding performance objectives for 1,000 years following facility closure. Additional calculations are also performed to address peaks that may occur at later times for use in the decision making process. The PA and other supporting documentation are subjected to an independent review from the Low-Level Waste Disposal Facility Federal Review Group (LFRG) and in many cases other external reviews are also involved.

Current PAs often involve a combination of probabilitistic and deterministic modeling to provide multiple lines of reasoning in order to best inform decision makers and identify key features of the total disposal system (engineered and natural) that significantly influence performance. Modeling results are used to assess compliance with performance objectives, to develop the design of the disposal facility and to provide the basis for waste acceptance criteria for the operating facility. Additionally, a PA maintenance program is required to regularly update analyses through additional experimentation and annual reviews to ensure that actual and potential conditions are assessed, reduce uncertainty for key parameters, and to continue to include new information from monitoring or field and laboratory studies. If a previously unanticipated event were to occur, the PA maintenance process includes procedures that are used to assess the need for facility operations to be modified in the future. This approach is similar to many aspects of the safety case concept being adopted internationally [2,3].

USDOE follows a “risk-informed, performance-based” approach to using PA to support decision making for waste disposal. The risk-informed concept reflects a graded perspective for interpretation of results. The NRC has described a "risk-informed" approach to regulatory decision-making as representing “a philosophy whereby risk insights are considered together with other factors to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety.” The term “performance-based” is used as an alternative to prescriptive requirements. The NRC describes a “performance-based” requirement as relying “upon measurable (or calculable) outcomes (i.e., performance results) to be met, but provides more flexibility to the licensee as to the means of meeting those outcomes.”

USDOE PERFORMANCE ASSESSMENT REQUIREMENTS

USDOE has required the use of LLW disposal PAs since 1988 to demonstrate compliance with performance objectives for the protection of human health and the environment. PAs address the future behavior of a disposal facility and the natural system as a tool to support decision-making. To fulfill this role, PAs are modeling evaluations using hypothetical, stylized scenarios based on reasonably conservative assumptions and simplifications to provide reasonable expectation of compliance rather than predictions of impacts to real people. The stylized scenarios are developed on a site-specific basis.

A major area of evolution for PAs is the increasingly significant role in identifying and prioritizing critical data/assumptions, facility design and model development needs and support the development of safe operating limits in addition to demonstrating compliance. In the early years, USDOE sites conducted PAs with various levels of detail and analysis, but often largely based on deterministic modeling. In the mid-1990s, USDOE developed PA guidance and through a continuous improvement program revised the process to take advantage of the newest modeling techniques, especially for sensitivity and uncertainty analysis, and the latest risk analyses. In the current revision of DOE Order 435.1 that is under development, the PA process has been enhanced again to provide more specific requirements and guidance to standardize the PA development based on experiences over the last 20 plus years. Examples of the information being included in the DOE Order 435.1 update are provided later.

One common element in the PA process since its inception has been the use of a graded and iterative philosophy for the modeling, which is consistent with international recommendations continuing today [3]. This approach places an emphasis on using the level of modeling detail necessary to make a defensible decision and focusing efforts to increase detail on areas expected to have the most influence on the decision. Some of the most significant advances in modeling have occurred in the implementation of sensitivity and uncertainty analysis to support efficient and defensible PAs.

The term “reasonable expectation” was intended to put the results of the PA in the proper context because a PA constitutes a projection of future events, not an absolute prediction of conditions that will occur in the distant future. Absolute compliance with performance objectives in the future cannot be demonstrated in the present. Rather, the intent of the PA is to provide a reasonable expectation, considering uncertainties in human evolution and behavior and engineered and natural systems over long time periods that the actual performance of the disposal facility will not result in exceeding the applicable performance objectives (i.e., the intent is to demonstrate that the dose will be less than a standard, rather than trying predict the actual dose).

During the development of DOE Order 435.1, USDOE factored in a 1997 report produced by the National Academy of Public Administration (NAPA) *, Deciding for the Future: Balancing Risks, Costs, and Benefits Fairly Across the Generations,* which addressed the issue of equity and fairness between current and future generations. The principles developed by the NAPA panel suggest that when looking far into the future, the major concern should be to avoid the possibility of catastrophic consequences to the public or the environment. For example, the panel believed that it would not be ethically appropriate to forego an activity which will provide many benefits to the current generation – and to the future generations as well – to avoid the possibility of limited consequences hundreds of years in the future. There are value judgments involved. The report notes that during the preparatory work and the panel's deliberations, the "near future" was considered to be on the order of 2 to 4 generations in the future, while the language "distant future" was thought of as referring to 500 to 1,000 years in the future. This time frame of several hundreds of years is also discussed in Publication 81 from the International Commission on Radiation Protection (ICRP) [4] in the context that "doses and risks, as measures of health detriment, cannot be forecast with any certainty for periods beyond around several hundred years into the future."

The NAPA report states that catastrophic risk should be defined incorporating notions such as increased risk levels, irreversibility, the scale of human activity, and the planetary impact of the project. The NAPA panel also articulates a Chain of Obligation Principle. Under the Chain of Obligation Principle the panel states that consideration of future generations does not entitle anyone to impose an injustice on the present generation. For implementing this principle, the Panel articulated a concept it called the "rolling present" wherein the current generation is not responsible to solve all the problems or eliminate all the risks for future generations but should provide the next succeeding generation the skills, resources, and opportunities to cope with any problems the current generation bequeaths. Likewise the next generation is obliged to do the same for the successive generations.

The USDOE risk-informed approach includes a time period for compliance with a numerical dose standard for USDOE's LLW disposal facilities. The approach considers the principles of intergenerational equity, uncertainties, and times of compliance used for other environmental protection requirements. In implementing its radiation protection responsibilities for LLW, USDOE also adopted a defense-in-depth approach that utilized geologic barriers, engineered barriers, numerous required passive and active institutional controls, and prospective analysis to guide decision making.

USDOE's multi-faceted defense-in-depth approach for assuring protection of the public health, safety, and the environment at LLW disposal facilities utilizes:

- Identifying and quantifying site characteristics which provide geologic and hydrologic barriers to radionuclide transport
- Facility design
- Waste acceptance requirements tailored to each specific site
- A rigorous waste generator certification program
- Federal ownership of the site and necessary buffer zones until no unacceptable hazard is presented by release of the site
- Barriers to intrusion
- Analyses projecting hypothetical performance of the facility PA and composite analyses
- Siting and design to minimize requirements for future maintenance
- A commitment to provide any future PA maintenance necessary
- Continued monitoring of facility performance
- Permanent maintenance of records

Although a PA and the comparison of the results of that assessment to an individual dose limit play an important role, they are part of what has evolved into a broader process that is based on a defense-in-depth approach. The USDOE protection system for LLW is based on the use reasonable assumptions and parameters in a compliance case for the PA to provide a reasonable expectation that the actual doses will not exceed the performance objectives for 1,000 years. In the USDOE system, sensitivity and uncertainty analyses are also conducted and the PA analysis time is extended beyond the time at which a compliance oriented comparison to a dose-based performance objective is made (1,000 years). These additional supporting analyses are used to support decision making and consider the possibility for catastrophic consequences at later times. Such calculations also provide insights as to which features and parameters are most important to performance. These insights are considered in the context of defining waste acceptance criteria and facilitating design optimization. This approach is similar to approaches being adopted internationally where the time after 1,000 years often includes provisions for the use of more qualitative metrics for comparison to support decision-making, including natural background levels and fluxes in the environment [3].

EVOLVING USDOE PERFORMANCE ASSESSMENTS

PAs have evolved over time based on lessons learned and as additional information has come available and modeling techniques have improved. Initial PA efforts were largely focused on a deterministic demonstration of compliance. Current PAs are part of a holistic process that integrates modeling, site characterization, laboratory studies, monitoring, public involvement and other activities into a collection of arguments to support decision making. The PA maintenance concept and the graded and iterative approach continue to be refined to help with the efficient use of resources, especially related to costly and time consuming activities like field and laboratory experiments (which provide some of the data to input into the model). The evolution of the modeling techniques and general methodology are the focus of this discussion.

Conceptual Site Model and Hazards Analysis

The conceptual site model approach includes the need to acquire meteorologic, topographic, geotechnical, and other environmental and human activity data to support decisions about the acceptability of a site for a LLW storage, treatment, and disposal facility, and to provide necessary input to the design of the facility, and specifically to the PA of a disposal facility. USDOE siting requirements prohibit locating LLW facilities at sites with environmental characteristics and geotechnical characteristics for which adequate protection cannot be provided through facility design (e.g., limiting radionuclides accepted, engineered barriers). This requirement further provides that LLW facilities “shall be sited to achieve long-term stability and to minimize, to the extent practical, the need for active maintenance following final closure.” During PA development, maintenance and revisions, this information is continuously updated and evaluated in the context of impacts on the PA conclusions, resulting in greatly enhanced conceptual site models

USDOE PAs place an emphasis on using the conceptual site model to form the initial basis for a hazards analysis of the facility and its environs. USDOE PAs have evolved to refine the conceptual site model with an emphasis on aspects with the greatest influence on the decision to be made. These influences include an identification of the hazards posed by the disposal facility and the barriers that can limit those hazards and assist in establishment of scenario development. This philosophy emphasizes developing an understanding of the total system and the role of different assumptions and barriers in terms of overall performance. Internationally, this focus on the understanding of the roles of different barriers in terms of performance has come to be referred to as a “safety functions” approach (e.g., [3]). This concept of starting from an understanding of the conceptual site model and safety functions of different barriers to establish the scenarios to be considered is referred to as a “top down” approach internationally [3]. Using this top-down approach as a starting point, more recently USDOE PAs have also been using approaches based on international lists of Features, Events and Processes (FEPs lists) as an audit tool to check for elements that may not have been addressed as part of the top-down approach. Internationally, this combined approach has been referred to as “top down, bottom up” [3] reflecting the fact that FEPs based approaches for scenario development have often been referred to as “bottom up” approaches.

In the 1990s and early 2000s, much international effort has advocated the use of “bottom up” FEPs based approaches for the development of scenarios (e.g., [5,6]). However, experience in USDOE assessments has suggested that a “top down, bottom up” approach starting from a conceptual site model and focusing on the roles of different barriers (safety functions) as part of the model is more effective. Recent international experience and feedback also supports the view that “top down, bottom up” approaches have been more effective in practical implementation [3]. In the USDOE PA guidance currently under revision, the conceptual site model and assessment of the effectiveness of different barriers is developed by the site, and incorporates a review by regulators and the public, and used for the basis for the scenarios and the models for potential contaminant release mechanisms.

Performance Objectives Associated with the Principal Exposure Pathways

DOE has established performance objectives that serve as the basis for demonstrating protection the public, environment and workers from releases of radioactive waste from the facility. USDOE PA dose coefficients are routinely updated to ensure the dose calculations to demonstrate compliance with the performance objectives are consistent with evolving international methodologies (see dose coefficient discussion below).

The performance objectives applied to each disposal facility are:

- Dose to representative members of the public shall not exceed 0.25 mSv (25 mrem) in a year total effective dose equivalent from all exposure pathways, excluding the dose from radon and its progeny in air**.**
- Dose to representative members of the public via the air pathway shall not exceed 0.10 mSv (10 mrem) in a year total effective dose equivalent, excluding the dose from radon and its progeny**.**
- Release of radon shall be less than an average flux of 0.74Bq/m^2/s (20 pCi/m^2/s) at the surface of the disposal facility. Alternatively, a limit of 0.0185 Bq/l (0.5 pCi/l) of air may be applied at the boundary of the facility.

Inadvertent Intruder Analyses

USDOE requires that PAs include hypothetical analyses to assess the potential impacts of a loss of institutional control. These inadvertent intruder calculations are considered when establishing the limits on concentrations of radionuclides for disposal. Consistent with recommendations of the ICRP [4], the expectation is that the analyses be based on reasonable activities for the inadvertent intruder using stylized scenarios assuming potential excavation of a basement and drilling of a well. While the implementation of this requirement has not changed much over time, there has been an increased emphasis on considering site-specific conditions and current practices when specifying site-specific scenarios. For example, where current well drillers would expect to drill through rock, engineered features such as concrete would not be considered an impediment to drilling. However, in locations with soils down to the aquifer, it can be assumed that a future inadvertent intruder well driller would stop drilling if they encountered reasonably intact engineered features like concrete. The use of one or more stylized scenarios for an inadvertent intruder is consistent with international recommendations. A basic drilling or excavation scenario is generally considered sufficient.

Receptor Location

The point of assessment for USDOE PAs corresponds to the point of highest projected dose or concentration beyond a 100 meter buffer zone surrounding the disposed waste or a different buffer zone can be used if properly justified based on regulatory agreements, formal land use policies or other considerations. This requirement is based on the need to establish a location for the purposes of performing prospective assessments of LLW disposal facilities. This approach of using seeking peak concentrations outside the buffer zone is consistent with the concept of protecting highly exposed individuals advocated by the ICRP.

Consideration of Reasonably Foreseeable Natural Processes

USDOE PAs address reasonably foreseeable natural processes that might disrupt barriers against release and transport of radioactive materials. The requirement addresses the need to account for recognized natural processes that will have an effect on the long-term performance of the disposal system. The modelers account for the possibility of degradation of the cover system, degradation of concrete, consolidation of waste materials, etc. The use of reasonably foreseeable events is consistent with the concept of demonstrating a reasonable expectation that the performance objectives will be met.

USDOE-approved Dose Coefficients

PAs use USDOE-approved dose coefficients (dose conversion factors) for internal and external exposure of reference adults. These are identified in DOE Order 458.1, *Radiation Protection of the Public and Environment*. The requirement addresses a need to provide consistency in the application of health physics practices in the development of prospective assessments. USDOE recently produced a Technical Standard [7] documenting the currently approved dose coefficients.

Base Case and Sensitivity/Uncertainty Analysis

In addition to calculations over the foreseeable future and the time of assessment (1,000 years), USDOE PAs also address peaks that could occur after 1,000 years for consideration as part of optimizing designs and as supplemental information for decision-making. The results of these calculations are included as part of the sensitivity and uncertainty analyses which provide additional support for a conclusion that the model is providing a reasonable projection and that there is not a catastrophic consequence in the far future. These longer term calculations address the need to ensure that there are no unexpected significant increases shortly after the time of compliance or catastrophic impacts at longer times and provide a mechanism for understanding the model performance and the significance of modeling parameters. The IAEA and ICRP have recognized that as results are obtained further out in time, there is a need to begin to take a more qualitative view when considering the relationship of the results with compliance oriented performance objectives. This recognizes that the concepts of dose and risk, as indicators of health detriment, cannot be forecast with any certainty for periods beyond around several hundreds of years [4] and the fact that there are significantly increasing uncertainties associated with events in the natural system and evolution of engineered features in the near surface environment after this time. The calculation of maxima provides additional information about the behavior of the model of the site and the system being modeled that would not be available if the calculations were truncated at the time of compliance. This additional information may be useful in evaluating alternative designs and maintaining radionuclide releases as low as reasonably achievable (ALARA).

Over time, the approaches to assess sensitivity and uncertainty have demonstrated the most significant improvements to USDOE PAs. Initially, USDOE relied on a limited collection of deterministic calculations based on known available information to demonstrate compliance and to support sensitivity and uncertainty analyses. As modeling improvements and uncertainty analysis tools have progressed over the past 20 years, USDOE now recommends that models include probabilistic calculations to consider uncertainties in multiple parameters. The term “probabilistic analysis” is used to refer to formal approaches for addressing uncertainty and sensitivity using distributions for input parameters (e.g., Monte Carlo approaches). The use of a combination of deterministic and probabilistic models has been termed a “hybrid” approach. The hybrid approach allows the use of more detailed models in a deterministic manner and provides for the more complete sensitivity and uncertainty analysis using the probabilistic approach. In the hybrid approach, it is generally necessary to identify the base case that will be used as the reference case, when placing emphasis on the deterministic model for compliance with specific performance objectives. Significant experience has been gained in the application of hybrid modeling, including the ability to conduct a combination of deterministic “base case” plus “what-if” sensitivity modeling and probabilistic uncertainty and sensitivity analysis. This hybrid approach provides a means to improve overall system understanding and the ability to capture possible but less probable assumptions in an efficient manner. The international community has also described the benefits of using a combination of probabilistic and deterministic models (e.g., [3]).

Such a combined approach provides an efficient means to address the great variety of potential changes to the climate, human behavior, environmental factors, and geological changes. By showing the analyses as a set of possibilities, decision-making is greatly improved. One of the areas of changing guidance for the analysis of the results of probabilistic analyses is specifying which set of results are used to compare with standards. USDOE advocates the use of the peak of the mean or median for probabilistic calculations when comparing future potential doses to a deterministic standard. While USDOE uses all of the information from the calculations, for calculations after 1,000 years, USDOE does not base decisions solely on the peak doses.

Decisions for results after 1,000 years are interpreted in a more qualitative manner as part of a risk informed approach to decision making in recognition of the significant increases in uncertainty in the far future.

As Low As Reasonably Achievable (ALARA)

PAs include a demonstration that projected releases of radionuclides to the environment shall be maintained ALARA. Requiring projected releases from a disposal facility to be as low as reasonably achievable is consistent with the concept that in addition to an assessment of compliance, a PA is to be used as a tool to aid in the development of facility design, waste acceptance criteria, and closure design. Consistent with the reasonableness portion of ALARA, projected doses or releases well below the performance objectives would require qualitative analyses to show that further reduction would not be reasonable. This has remained fairly unchanged over time.

Impact to Water Resources

For purposes of establishing limits on radionuclides that may be disposed of near-surface, PAs include an assessment of impacts to water resources. This requirement addresses the need to ensure that water resource protection is considered in the disposal of LLW and to establish inventory controls for waste that can be disposed of in the near surface. USDOE PAs are required to consider applicable Federal, State and local requirements for drinking water and groundwater protection.

Waste Acceptance Criteria

The waste acceptance criteria for a disposal facility is the document in which limitations or other requirements are imposed as a result of the PA and other requirements associated with the waste to be disposed. The PA provides a risk informed, performance based link between the waste form/container and the long-term performance of the facility. Specific hazards are identified in development of a disposal facility’s waste acceptance criteria and include high hazards to the workers and the environment in the short-term from acceptance of waste containing unacceptable materials, and potential for impacts in the long-term to the disposal facility performance.

USDOE waste acceptance criteria are developed on a site- and facility-specific basis and evolve over time in the context of the PA maintenance process as new data are obtained. Waste acceptance criteria are established on a radionuclide-specific basis and multiple criteria can also be established for a radionuclide that may be disposed in different forms or containers. Evolution of waste acceptance criteria is often a result of considering the isolation capabilities of specific waste forms or containers that were not specifically addressed in the original PA. For example, the allowable amount of C-14 that is disposed as a general waste can be different than the amount that would be allowed in a cementitious waste form or container. The PA is used to establish the different limits considering the performance of the waste form or container as a means to reduce the release of C-14.

Performance Assessment Maintenance

USDOE recognized more than 20 years ago that once a PA was developed, new information should continue to be gathered after implementation to verify that the performance objectives continue to be met and to address outstanding uncertainties. The requirement to maintain a PA addresses the need to keep the analyses supporting the authorization basis for the facility up-to-date. While this requirement has existed since USDOE began conducting PAs, it has increased in significance over time and has become more effective and efficient as improved approaches for sensitivity analysis have been implemented. In addition to the requirement being associated with receiving waste streams with characteristics not considered in the original PA, it has also been recognized for its importance in planning and assessing research needs on the disposal facility operational practices including waste form, waste placement, and best practices for monitoring. The advantages of updating an analysis based on a better understanding of the performance of a disposal system component include improved confidence and providing a more defensible basis for assumptions. The requirement also addresses potential changes in decisions about remediating other sources of radioactivity that may contribute to the dose projected for the disposal facility.

An additional requirement under PA maintenance recognizes the need for the field organization to make routine determinations of the acceptability of the PA. The requirement facilitates integration of documents important to safety (potential conditions that may occur in any one area important to authorization basis may affect another area).

A further benefit of PA maintenance is the recognition that at times it may be necessary to revise an existing PA. By performing PA maintenance activities, it becomes clear when the existing assessment is outdated due to a preponderance of new information triggering the update. An updated USDOE PA includes evaluating all aspects of the assumptions used in the current PA, recalculating all the doses identified in the performance objective, and providing a new analysis of performance. These are typically conducted every 5-10 years depending on the identification of significant new information or other changes such as proposed new designs of disposal facility cells. The testing and research is designed to improve confidence in modeling results. Additionally, because disposal facilities may be requested to accept certain waste streams that were not specifically considered in the original PA, supplemental analyses may be necessary to evaluate whether the waste can be safely disposed. During the revision process, these supplemental analyses are incorporated in the updated PA. This requirement promotes performance-based management of the PA maintenance activity by not demanding a revision on a set timetable, but allowing a decision to be made based on need.

Performance Assessment Oversight

Once the PA has been developed, it is typically reviewed by a peer review group at the USDOE site. This site review often results in several rounds of questions and changes to improve the PA. Once a PA is approved at the site level, the PA is sent to USDOE Headquarters for review by the LFRG. The LFRG charters a team of experts from other USDOE sites, industry, and academia to conduct an in-depth review typically involving 6-8 weeks of paper review and one week of on-site review. The LFRG review team identifies findings and the site must respond to the findings prior to the team recommending approval by USDOE Headquarters management. Findings can result in significant changes required to the PA and in modifications to the maintenance plan. Development of a PA is not an insignificant undertaking. The process of developing and approving a PA often requires multiple years.

Once all pieces of the disposal analyses are conducted, USDOE Headquarters issues a Disposal Authorization Statement which is the USDOE equivalent to an NRC license. This requirement addresses a programmatic management need to ensure that prior to committing significant resources to the development and construction of a disposal facility, there is a reasonable expectation the facility will accept the projected waste streams, and provide protection of the future public and the environment. If an existing PA is revised, a new Disposal Authorization Statement is required to be issued, specifying any new limits and conditions on construction, design, operations, and closure of the LLW facility.

CONCLUSIONS

The USDOE approach for conducting PAs has evolved over the past 20 years from performing relatively simplistic deterministic calculations to a holistic PA process for providing a sound basis for the safe disposal of radioactive waste. Improvements to PA modeling includes: the use of more sophisticated models, a combination of deterministic and probabilistic modeling, integration of modeling with monitoring for confidence building, and integration with research and development and field studies to better quantify uncertainties and optimize designs. The use of a “hybrid” approach to modeling (deterministic and probabilistic modeling results analyzed in conjunction) has proven effective to address computational limitations and the need for simplifications to be able to conduct the many simulations associated with a probabilistic approach. The benefits of approaches that take advantage of combinations of deterministic and probabilistic analyses have also been described in recent international recommendations [3].

In addition to modeling improvements, there are a number of other developments that have become relatively standard practice. PAs are based on a total systems approach for development of scenarios to be considered, starting with development of a conceptual site model, and including evaluation of performance with an emphasis on identifying the roles and significance of different barriers (e.g., safety functions). The use of a "top-down, bottom-up" approach for scenario development has proven to be effective and efficient. The PA maintenance concept has been formalized into an integrated process which provides a direct link to a research and development program and monitoring activities. The PA maintenance concept has also been institutionalized with the iterative process of annuals reviews and improvements through PA revisions as assumptions and information are updated over time. The USDOE approach is also consistent with recent recommendations from the international community [2,3], including the use of the safety case concept which provides a useful construct for taking credit for all of the activities that support the demonstration of safety in addition to the PA.

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