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A Performance Assessment Methodology For Low-Level Radioactive Waste Disposal[1]

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ABSTRACT

To demonstrate compliance with the performance objectives governing protection of the general population in 10 CFR 61.41, applicants for land disposal of low-level radioactive waste are required to conduct a pathways analysis, or quantitative evaluation of radionuclide release, transport through environmental media, and dose to man.

The Nuclear Regulatory Commission staff defined a strategy and initiated a project at Sandia National Laboratories to develop a methodology for independently evaluating an applicant's analysis of postclosure performance. This performance assessment methodology was developed in five stages: (1) identification of environmental pathways, (2) ranking the significance of the pathways, (3) identification and integration of models for pathway analyses, (4) identification and selection of computer codes and techniques for the methodology, and (5) implementation of the codes and documentation of the methodology.

The final methodology implements analytical and simple numerical solutions for source term, ground-water flow and transport, surface-water transport, air transport, food chain, and dosimetry analyses, as well as more complex numerical solutions for multidimensional or transient analyses when more detailed assessments are needed. The capability to perform both simple and complex analyses is accomplished through modular modeling, which permits substitution of various models and codes to analyze system components.

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INTRODUCTION

Under the Atomic Energy Act, as amended, the NRC and Agreement States license land disposal of low-level radioactive wastes (LLW) using the requirements of 10 CFR 61 or comparable state requirements. To demonstrate compliance with the performance objective in 10 CFR 61.41 governing protection of the general population from releases of radioactivity, applicants for disposal of LLW are required to conduct analyses for specified environmental pathways for potential radionuclide release away from LLW disposal facilities. A performance assessment is a quantitative evaluation of radionuclide release, transport through environmental media, and dose to man, and comparison of dose estimates to regulatory performance objectives.

The U. S. Nuclear Regulatory Commission (NRC) staff defined a strategy (Starmer et al., 1988) and initiated development of a methodology at Sandia National Laboratories (SNL) to be used by NRC staff for evaluating independently applicants' analyses of post-closure performance. The performance assessment methodology was developed in five phases, including (1) identification of post closure environmental pathways, (2) ranking the significance of pathways, (3) identification and integration of models for pathways analyses, (4) identification and selection of codes and techniques for the methodology, and (5) documentation of the methodology and implementation of codes. The purpose of this paper is to summarize regulatory requirements for performance assessment in LLW licensing, a strategy for conducting performance assessments to support reviews of LLW license applications, and the NRC's performance assessment methodology for conducting confirmatory analyses.

RELEVANT REQUIREMENTS

The performance objective in 10 CFR 61.41 states that concentrations of radioactive materials released to the general environment via groundwater, surface water, air, soil, plants, or animals must not result in an annual dose exceeding an equivalent of 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ to any member of the public. In 10 CFR 61.13 (a) applicants are required to conduct pathways analyses including air, soil, groundwater, surface water, plant uptake, and exhumation by burrowing animals to clearly demonstrate there is reasonable assurance that the exposure limits of 10 CFR 61.41 are not exceeded. To show compliance with performance objective in 10 CFR 61.41, license applicants must conduct a site specific performance assessment to demonstrate that the maximally exposed individual will not be exposed to radionuclide releases that result in doses equivalent to or exceeding the specified dose limits.

The performance objective in 10 CFR 61.42 states that the design, operation and closure of land disposal facilities must ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste at any time after removal of active institutional controls over the disposal site. This is accomplished in 10 CFR 61 through the use of a waste classification scheme that requires improved intruder protection for the more highly active Class B and Class C wastes. In 10 CFR 61.13 (b) applicants are required to conduct analyses to demonstrate that there is reasonable assurance that the waste classification and segregation requirements will be met and that adequate barriers to inadvertent intrusion will be provided.

A demonstration of intruder protection would normally consist of an analysis of the longevity of materials used as intruder barriers, and of long-term stability when depth of burial is used as intruder protection medium. Performance assessment would not be required to demonstrate compliance with 61.42 when the waste classification scheme of 10 CFR 61 is followed and waste segregation, site stability, and intruder protection measures stipulated in the regulation are met (Starmer, 1988). If, however, an applicant requests an exemption from the waste classification scheme in 10 CFR 61, a site-specific performance assessment consisting of intruder scenarios and dose analyses would be required to demonstrate adequate protection for an inadvertent intruder.

In addition, another relevant requirement includes 10 CFR 61.51 (a) (2) which states that the disposal site must be capable of being characterized, modeled, analyzed, and monitored.

NRC's PERFORMANCE ASSESSMENT STRATEGY

Starmer et al. (1988) describe a preliminary strategy for reviewing post-closure performance assessments in support of license applications for LLW disposal relative to the technical requirements and performance objectives in 10 CFR 61. This paper summarizes important aspects of NRC's current performance assessment strategy including the specific models, codes, and techniques contained in the performance assessment methodology for LLW disposal facilities developed by SNL (Kozak et al., 1990b). The NRC staff is in the process of developing guidance on specific performance assessment issues that have heretofore not been addressed. Further discussion of these specific performance assessment issues is outside the scope of this paper.

Components of Performance Assessment

Performance assessment for commercial LLW disposal involves analyses of the future behavior of a LLW waste disposal system and its impacts on man and the environment, followed by comparison of modeling results to the regulatory performance objectives in 10 CFR 61. The NRC staff considers that an integrated performance assessment should include (1) a description of the natural and engineered features of the disposal system, (2) identification of pathways, processes and events that may affect facility performance, (3) quantification of impacts using pathways modeling, including treatment of associated uncertainties, and (4) comparison of modeling results to regulatory requirements (OECD, NEA, 1990).

Performance assessment cannot be used to demonstrate unequivocally that a site will be safe; rather, it is a technique for examining factors that may affect site safety and providing a basis to assess whether reasonable assurance exists that a site will meet performance objectives (OECD, NEA, 1990). Estimated doses are calculated for comparison to performance objectives and are considered to be indicators of safety, rather than absolute predictions of doses that may be received by members of the general public (OECD, NEA, 1990). In this way, there can be confidence that a site meets regulatory performance objectives even though there is uncertainty in the estimated doses (Kozak et al., 1990).

Development of a Conceptual Model

A sufficient understanding of relevant physical and chemical properties of the disposal system and their evolution is a prerequisite for conducting quantitative modeling (NRC, 1990). Site-specific data are needed for model input parameters and for developing one or more conceptual models of the subsurface. The applicant must collect sufficient data to understand the physical system in order to defend simplifying assumptions of the model.

In developing a conceptual model of the disposal system, the applicant should identify a complete set of possible pathways for radionuclide release, and describe important release scenarios, which are postulated circumstances or events that might affect site safety. An example of this type of scenario includes the gradual degradation of engineered barriers of the system. Such scenarios should include a combination of anticipated and unanticipated events and processes, both natural and human induced. The applicant should eliminate those pathways and scenarios which are trivial, restricted, or obviated by other pathways and explain the process used to eliminate potential pathways. The remaining set of defensible pathways and release scenarios represents a large part of the conceptual model of the waste disposal system (Starmer et al., 1988). The remaining aspects of the conceptual model consist of an abstraction of site characterization data into a form that can be modeled (Kozak et al., 1989). Simplifications must generally be made about many aspects of the system, including system geometry, spatial and temporal variability of parameters, and isotropy of the system.

In general, the degree of complexity of the conceptual model should be determined from the goals of the modeling (NRC, 1990). A simple conceptual model may be fully adequate if it provides satisfactory confidence in site performance (Kozak et al., 1990b).

Quantitative Modeling

Based on the conceptual model of the system and postulated circumstances that could affect the overall safety of the site, the applicant should quantitatively analyze site performance to estimate doses to maximally exposed individuals and to demonstrate compliance with performance objectives (Starmer et al., 1988). Applicants' analyses should be supported by modular modeling consisting of appropriate submodels that reflect the conceptual model. Typical submodels are infiltration, leaching, near-field transport, groundwater and surface water transport, atmospheric transport, plant and animal uptake, and human dose. Performance assessment should provide a calculated equivalent annual dose to the maximally exposed individual with corresponding maximum and minimum values (Starmer et al., 1988).

A predictive model should be developed with the purpose of bounding the behavior of a system to demonstrate with sufficient understanding and confidence that regulatory criteria will be met. Even though site-specific data form the basis for quantitative models, such models should not be expected to realistically represent the actual system. However, the applicant must have sufficient data to bound the ranges of parameters and boundary conditions and construct a defensible model of the subsurface environment. This in turn facilitates the applicant in defending the models's simplifying assumptions and model conservatism.

The results of predictive models should be evaluated with other information to make regulatory decisions about site safety. Other factors may include operational experience, and the qualifications of those individuals collecting site-specific data, conducting performance assessments, and interpreting model the results

Uncertainties and Sensitivities

Long-term predictions of site performance are extrapolations from known conditions, thus performance assessments should include quantification of uncertainties associated with dose estimates and analyses of the sensitivity of the model results to the known input parameters and model assumptions. Uncertainties in performance assessment result from three general sources: (1) data and parameter uncertainty, (2) scenario uncertainty (postulated circumstances affecting site safety over time), and (3) modeling uncertainty. Modeling uncertainty is further subdivided into (1) conceptual model uncertainty, (2) mathematical model uncertainty, and (3) computer code uncertainty (Bonano and Cranwell, 1988).

Stochastic modeling may be used to assess uncertainties associated with data and parameter uncertainty, such as heterogeneities of the waste, design-specific engineered barriers, and site-specific hydrogeology units. However, because of the deterministic nature of data gathering, the uncertainty associated with how conservative or representative a given conceptual model may be is more difficult to quantify, as are the scenarios, and the assessment of their consequences (Bonano and Cranwell, 1988).

An approach for dealing with performance assessment uncertainty is to use a bounding analysis where the scenarios, models, and parameters are demonstrably conservative to enable a more simplistic assessment. In this way uncertainties that are not important to the overall safety demonstration can be screened out of the licensing process (OECD, NEA, 1990). Site-specific data are needed to provide bounds on ranges of parameters and boundary conditions to minimize uncertainty associated with results (NRC, 1990). Sensitivity analyses should be used to show which parameters or uncertainties are important to demonstrate compliance with performance objectives, hence which data are most crucial to collect. This may in turn indicate additional site specific data that must be collected. Thus performance assessment must be viewed as an iterative process of data collection, conceptual model development/modification, and model application (OECD, NEA, 1990). The iterative process contributes to an understanding of conceptual model uncertainty, the conservative nature of analyses, and confidence and defensibility in the overall analyses.

Review of Performance Assessments

The burden of proof in demonstrating compliance with the requirements in 10 CFR 61 resides with the license applicant. The NRC staff independently evaluates facility performance relative to the performance objectives in 10 CFR 61 by confirming or verifying the assumptions and conclusions supporting applicants' analyses. The NRC staff may conduct confirmatory analyses using the models, codes and techniques implemented in the performance assessment methodology developed by Kozak et al., (1990b).

In accordance with Chapter 6 of the NRC's Standard Review Plan for LLW License Applications (NRC, 1988), in evaluating analyses of various environmental pathways, the NRC staff will critically review and comment on applicants' performance assessments, focusing on (1) representation of the physical system, (2) integration of individual analyses with other system component analyses, (3) basis for selection of model input, (4) model execution and underlying assumptions, (5) analysis of uncertainties and sensitivities, and (6) use of modeling results in support of the compliance demonstration. The amount of independent modeling to be conducted by NRC staff is determined based on expert judgement, the significance of uncertainties associated with model assumptions and results, and degree of confidence in the models and codes used by the applicant (Starmer, 1988).

The minimal independent action that the NRC staff may take is reviewing an applicant's modeling, making comments, and evaluating whether the applicant's responses to the comments provide reasonable assurance that the performance objectives will be met. Preparation of comments does not necessarily require NRC staff execution of performance assessment codes.

In contrast, the maximum independent action that the NRC staff can take is to conduct independent modeling of all pathways using the codes and techniques in the NRC's performance assessment methodology. Alternatively, the NRC staff may use the methodology to analyze subsets of the applicant's analyses and test individual assumptions. The NRC staff is likely to perform relatively simple and conservative assessments to evaluate the validity of the overall modeling results. Simple models and codes embodied in methodology are preferred for confirmatory analyses as long as their use can be defended considering the full disposal facility (Starmer et al., 1988).

In general, reasonable conservatism should be folded into performance assessments from the beginning (Starmer et al., 1988). If a bounding conservative model can be used to demonstrate compliance, then realistic analyses are not necessary (NRC, 1990). A simple deterministic modeling approach is preferred for its efficiency, cost effectiveness, and defensibility (Starmer et al., 1988).

In reviewing modeling results, the NRC staff will evaluate whether the applicant's performance assessment provides reasonable assurance of compliance with the regulatory requirements (Starmer et al., 1988). In addition, staff will assess whether the applicant has provided sufficient data to support the simplifying assumptions of the analyses and to support the conceptual model of the disposal system. In addition, staff will ensure that all pathways have been considered and that all factors affecting site safety have been quantitatively analyzed and justified as to why they need not be considered in the compliance demonstration. The NRC staff will check if the applicant has adequately incorporated into the results inherent uncertainties stemming from characterization of input parameters, simplifying modeling assumptions, and computational methods (Starmer et al., 1988). The results of analyses should incorporate maximum and minimum ranges of dose to the maximally exposed individual, and discuss the reliability of predicted results due to uncertainties of input data and analyses. In addition, dose estimates should be presented as a function of time, considering half-lives of specific radionuclides and expected waste inventories and durability of natural and engineered barriers (Starmer et al., 1988).

The NRC staff will ensure that all codes used by the applicant to support the license application should be sufficiently documented, verified, and benchmarked in accordance with NUREG-0856 (NRC, 1983) so that technically competent reviewers can successfully reproduce the performance assessment modeling and develop comparable, defensible results. Data collection and modeling should be performed using an acceptable quality assurance plan following the guidance provided in NUREG-1293 (NRC, 1989). Models should also be calibrated using available site-specific data (Starmer et al., 1988).

OVERVIEW OF THE METHODOLOGY

The tool that NRC staff will use to conduct independent evaluations, and to evaluate sensitivities and uncertainties in the analysis, is the performance assessment methodology developed at SNL. The methodology is intended to be capable of analyzing several different types of disposal facilities in a potentially wide variety of geological and climatic settings (Kozak et al., 1990b). This need for flexibility is a primary characteristic of the methodology, and is reflected in its modular structure. In the modular approach to performance assessment, the methodology consists of a more or less loosely grouped collection of computer codes for different parts of the analysis that require some user interaction to provide data interfaces between the codes. By contrast, in a systems code the data interfaces are accomplished internally to the code, and the way in which the interface is accomplished is hidden from the user and unchangeable.

The primary modules considered in the methodology are ground-water flow, source term, ground-water transport, air transport, surface-water transport, food chain, and dosimetry. Other effects, such as biointrusion, can be analyzed using the methodology, but are not considered to be of primary importance (Shipers and Harlan, 1989). The food chain and dosimetry modules are fairly standardized, as embodied in NRC Regulatory Guide 1.109 (NRC, 1977) and ICRP Publication 26 (ICRP, 1977). As a result, there is only one method for food chain and dosimetry analyses in the methodology. By contrast, for each of the other modules in the methodology, either a simple analysis or a more complicated analysis can be chosen. For example, in the ground-water flow and transport modules, the analyst can use either simple one-dimensional steady-state semi-analytical solutions for homogeneous media, or more a elaborate numerical analysis, which can account for transient phenomena in a variety of heterogeneous media with a variety of boundary conditions.

The flow analysis must account for flow in both the saturated and unsaturated (vadose) zones. A moisture-barrier cover is usually included as part of the design of a low-level waste facility, which complicates the vadose-zone flow analysis. Designs for cover systems typically include several soil layers that provide low permeability coupled with high capillarity (Herzog et al., 1982). Flow through such barriers is intrinsically multidimensional, since the purpose of the engineered cover is to laterally divert a vertical flow rate. Consequently, it is usually necessary to use multidimensional analysis to determine the optimum performance of the cover. If one-dimensional analyses are used in the performance assessment, it is necessary to compare these with a multidimensional model of the cover to demonstrate that the one-dimensional model provides a satisfactory representation of the cover behavior. VAM2D (Huyakorn et al., 1989) has been recommended for the flow analysis in this methodology. This code has considerable flexibility in the types of boundary conditions that can be specified, and has been found to contain robust numerical methods (Kozak et al., 1990a).

Source term analyses must contain components that analyze the failure of structures and containers, the leach rates of radionuclides, and the transport of those contaminants to the boundary of the disposal unit. Failure of concrete structures is modeled in this methodology as a delay time to the onset of releases. There is no adequate existing model to analyze the details of failure of concrete structures to estimate the failure time or the mode by which they fail. Instead, currently available models are only adequate to make qualitative comparisons between types of concrete (Clifton and Knab, 1989).

One of two methods can be used to analyze the breach rate of waste containers in the methodology. A simple approach can be used, in which the failure of containers is modeled as a delay time to the onset of releases. Alternatively, the method of Sullivan et al. (1988) can be used to analyze the breach of carbon-steel containers. This method uses a semi-empirical model for pitting and general corrosion rates, with empirical parameters determined from generic subsurface corrosion data. The advantages and drawbacks of this approach have been discussed in detail by Sullivan et al. (1988) and by Kozak et al. (1989). This method for determining container corrosion is incorporated into the BLT (Breach, Leach, and Transport) computer code (Sullivan and Suen, 1989).

There will often be large uncertainty in modeling the leach rates in the disposal unit. This uncertainty arises from the large number and variety of waste types and forms in low-level waste, and from the complex chemistry of interaction between waste constituents and their surroundings. As a consequence of this uncertainty, an approach should generally be used that provides confidence in the conservatism of the source term analysis.

One approach that can usually be considered conservative is to use a surface-wash leaching model. In this model it is assumed that the waste resides at the waste form surface, and is immediately available to be washed off by passing water. The idea behind the model is that mass-transfer limitations are neglected, which leads to rapid predicted releases. This modeling approach is particularly appropriate for use in modeling releases from unstabilized waste, since unstabilized waste is particularly uncertain in chemical form and physical structure. For stabilized waste forms in which convection can be neglected, a diffusion-limited leach rate is appropriate (Sullivan et al., 1988; Matsuzuru and Suzuki, 1989), and such a model has been incorporated into the methodology.

A simple analytical source-term analysis has been developed for use in the methodology that is based on a mixing-cell model, but which incorporates dispersion in the disposal unit in a simplified manner (Kozak et al., 1990a). Either surface-wash or diffusion-limited leaching releases can be modeled. This simple source-term model provides analytical estimates of releases from the disposal unit, and retains much of the flexibility of more complicated analyses. However, more detailed source-term models have been retained in the methodology in the form of BLT (Sullivan and Suen, 1989).

Both simple and more complicated codes are included analyzing ground-water flow and transport. A Green's function solution is used for simple analyses of ground-water transport. The solution method is strictly valid for constant one-dimensional aquifer flow in an isotropic aquifer of constant or infinite thickness. However, the method can often be used to conservatively approximate ground-water concentrations when these criteria are not strictly fulfilled by using conservative estimates of parameters in the model. Similar solutions have recently been recommended for use in low-level waste performance assessment applications (Rood et al., 1989; Matsuzuru and Suzuki, 1989). The Green's function solutions and the simple source-term model have been combined in a program called PAGAN (Performance Assessment Ground-water Analysis of low-level Nuclear waste), which provides a simple menu-driven input and output structure for the analysis (Chu et al., in press). More complicated ground-water transport analyses can be performed in the methodology using BLT (Sullivan and Suen, 1989) or VAM2D (Huyakorn et al., 1989). Complications in the analysis may include transient and multidimensional flow fields, and complicated boundary conditions.

The results from these codes can be used as input to analyses of surface-water transport, air transport, and food-chain and dosimetry. The computer code GENII (Napier et al., 1988) has been recommended for use in the methodology for these pathways. GENII contains both simple and more complicated modeling approaches for both surface-water transport and air transport analyses, which is in keeping with the philosophy of retaining the flexibility to analyses in more than one way.

The result of the performance assessment analysis is a series of dose histories for each radionuclide of importance. The contribution of each radionuclide to the dose must then be added together to produce the total predicted dose. This dose estimate is intended to be compared with the regulatory performance objectives in 10 CFR Part 61.41. Estimated doses are not intended to reflect actual doses that may be received by members of the general public.

ONGOING WORK

The NRC staff has initiated a project at Pacific Northwest Laboratories (PNL) to test the individual techniques and codes of the methodology using existing site databases and compare codes of the methodology to other codes for each pathway. The result of this work will become available in 1992 and 1993 and will be used to update and refine the methodology. In addition, NRC staff has contracted with Brookhaven National Laboratories (BNL) to develop a source term methodology that allows for more realistic assumptions than used in NRC's current approach, but less mechanistic and data intensive than needed for the BLT code developed by BNL. The result of BNL's work will be available in 1993 and will be incorporated into the methodology. Sandia National Laboratories (SNL) has begun a project to update and improve the methodology using the products of other NRC contractors as they become available. SNL will recommend to NRC an approach for treating uncertainties in the methodology, and evaluating existing models and codes to treat breaching of engineered barriers. This work will also be incorporated into the methodology in 1992 and 1993. Finally, the NRC staff is expanding its strategy for performance assessment to include guidance on key performance assessment issues imbued in the licensing process. This guidance should be available in 1992.

SUMMARY

This paper summarizes the NRC approach for conducting evaluations of license applications for low-level radioactive waste facilities. Discussions are provided on the overall strategy to be used by NRC staff in performing the evaluations, and on the specific modeling approaches to be used in conducting the evaluations. The methodology is still evolving, and improved modeling approaches are under development.

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