UPDATED RECOMMENDATIONS FOR LOW-LEVEL WASTE PERFORMANCE ASSESSMENT*

Matthew W. Kozak and Natalie E. Olague
Safety and Risk Assessment Department
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

A low-level radioactive waste performance assessment methodology was developed by Sandia National Laboratories for use by the U.S. Nuclear Regulatory Commission in evaluating license applications under 10 CFR Part 61. The purpose of the methodology is to allow confirmation of a licensee's evaluation of postclosure impacts, to provide reasonable assurance that the performance objectives in 10 CFR Part 61.41 are met.

Subsequent work has been undertaken to update and improve the methodology where necessary, and to build confidence in the models in the methodology. Since developing the methodology, it has been applied several times to test cases. This additional experience allows an improved assessment of the modeling needs. This paper assesses the adequacy of the current models, and identifies additional models that may be useful to include in the methodology. Models that have become available since the preparation of the original methodology are discussed. In addition, a formal process for low-level waste performance assessment and treatment of uncertainty is recommended, and model validation is examined.

INTRODUCTION

A low-level radioactive waste performance assessment methodology was developed by Sandia National Laboratories (SNL) for use by the U.S. Nuclear Regulatory Commission (NRC) in evaluating license applications under 10 CFR Part 61 (1). The purpose of the methodology is to allow NRC to confirm a licensee's evaluation of postclosure impacts. These performance assessment analyses are the basis for providing reasonable assurance that the performance objectives in 10 CFR Part 61.41 are met. The methodology must be flexible enough to handle a wide range of potential low-level waste disposal facilities. The performance assessment modeling may range from being very simple, to being rather more complex, and models are included in the methodology for both of these possibilities. Since the methodology is modular, the analyst may substitute more complicated models for only part of the analysis when appropriate. This paper is an update to earlier work, described in Shipers (2), Shipers and Harlan (3), and Kozak *et al.* (1,4,5,6), as well as other pertinent documents on low-level waste performance assessment (*e.g.*, Starmer *et al.*, 7; Deering and Kozak, 8). The update is a work in progress. The recommendations given here will form the general directions toward which the methodology is heading, but some of the specific approaches may continue to evolve.

GENERAL CONSIDERATIONS

We have previously introduced a formal approach to treating uncertainties for low-level waste performance assessment (9); these recommendations were different than earlier guidance on the treatment of uncertainty. The formal uncertainty analysis has several salient characteristics. Parameter uncertainty should be addressed by Monte Carlo analysis. For the sake of efficiency, it is recommended that Latin Hypercube Sampling should be used to reduce the number of realizations needed. Conceptual model uncertainty should be addressed by including a broad set of conceptual models in the analysis. The most conservative of the conceptual models that cannot be eliminated based on site-specific information should be compared with the regulatory requirements. Conservatism here is defined *after* all models have been analyzed, not before. The most difficult issues in low-level waste performance assessment uncertainty analysis are related to future uncertainties. The resolution of these issues is a regulatory matter, not addressed here.

The primary purpose of low-level waste performance assessment is to provide a technical basis to support a confident regulatory decision about compliance of the disposal facility with the performance objectives in 10 CFR Part 61.41. Regulatory confidence is different than scientific confidence within the context of performance assessment. There may be significant uncertainty in predicting in an absolute sense the maximum future dose: this is scientific uncertainty. In contrast, regulatory confidence is concerned with information that may influence the regulatory decision. Scientific uncertainty may be irrelevant to making a regulatory decision, provided that there is a confident upper bound to the doses, and provided that regulatory requirements are met. In such a case, there is adequate confidence in the regulatory decision even if there is large scientific uncertainty about absolute predicted doses. Therefore, the objective of performance assessment is to minimize the likelihood of making a bad regulatory decision. The analyst should strive for minimal likelihood of accepting a site that in actuality will not meet the performance objectives.

In passing, we note that classical validation studies are generally directed toward minimization of scientific uncertainty. Such studies therefore may be of limited use in developing confidence in regulatory decisions, and are considered to be completely separate processes from performance assessment. Independent validation exercises provide confidence in performance assessment only to the extent that they expand current fundamental scientific understanding of processes that might be occurring at a site. Such studies may play

* This work was supported by the U.S. Nuclear Regulatory Commission and performed at Sandia National Laboratories, which is operated for the U.S. Department of Energy under contract number DE-AC04-76DP00789.

a role in building confidence in future performance assessments, but have little bearing on today's activities. Scientific progress is slow, and performance assessments must be (and can be) conducted using current knowledge. Validation exercises directed toward regulatory decisions do not generally produce confidence that can be transferred between sites (10).

Kozak (11) has developed a decision analysis approach to low level-waste performance assessment that uses uncertainty analysis in a formal manner to reduce regulatory uncertainty. A full discussion of the process is outside the scope of this paper, so only a brief summary is given here. The process is iterative, in which models and parameters are developed that are conservative relative to existing information about the site. Since the models are designed to be conservative, they may not rigorously represent the specific behavior of the system, but instead produce calculated doses exceeding those that the actual behavior of the system will produce. At all stages of the process, modeling is conservative relative to existing knowledge about the facility. Subsequent iterations serve to relax conservative assumptions through the introduction of new information. Thus, site characterization activities can be focused on those areas which are critical to performance assessment; that is, areas critical to providing regulatory confidence.

A key to developing regulatory confidence is to invite participation by all interested stakeholders. In using this approach, regulators, developers, the public, and interveners would all have the opportunity to assist in developing conceptual models of the disposal facility. The concerns of all participants would be addressed as part of the iterative process, by successively screening models that result in doses exceeding the performance objectives. After a number of iterations of performance assessment, the licensing process can proceed using models with which all interested parties are comfortable.

Defensibility of the analysis is intrinsically produced as part of the process. For each specific site, confidence is built by progressing from very conservative models toward less conservative models as the amount of available information increases. The primary components of the defensibility of the analysis are 1) the iterative nature of the process, in which confidence is built as subsequent iterations are performed, 2) integration with site characterization activities, such that data collection is focused on issues that have the most significant impact on reducing *regulatory* uncertainty, 3) the use of formal uncertainty analysis, 4) the participatory process, which provides for eliminating biases and establishing a complete range of potentially adverse conditions, 5) decreasing conservatism only based on new information, and 6) the visibility of the process in showing how alternative modeling assumptions have been refuted or supported.

REVISED MODELING RECOMMENDATIONS

A general area in which modeling in the methodology could be improved is in user friendliness. At the present time, a significant amount of skill in using codes is required to implement the methodology. In addition, using the methodology can be time-consuming and tedious. Consequently, automated interfaces within a computer framework are being developed between codes in the methodology. It is crucial to maintain the flexibility of the methodology, hence multiple interfaces will be developed to provide the requisite flexibility.

Ground-Water Flow and Transport Modeling

A specific method for evaluating infiltration was not included in the original methodology; it was concluded after a literature review that a sufficiently general method was unavailable (12,13). Instead, it was suggested that the licensee should support infiltration estimates with a combination of site-specific data and modeling. There have been no significant changes in the state of the art since then that would change this recommendation. Nevertheless, specific modeling approaches for infiltration are needed in the methodology. At the current time, a basis for choosing one approach over another is not available. Consequently, it is recommended that a comprehensive comparative analysis be conducted to assess existing models (14).

To model ground-water flow and transport, the original methodology contained the computer codes PAGAN (6,15) and VAM2D (16). However, VAM2D is a proprietary code and may have some quality assurance problems. A number of possible alternatives to VAM2D have recently become available. Of these, VS2DT (17,18) has been identified as the most promising replacement for VAM2D in the methodology.

In the original development of the methodology, preference was given to codes that were able to model variably saturated media; that is, either saturated or unsaturated media. It has since become clear that this constraint was useful in reducing the number of codes needed in the methodology, but also introduced limitations. Consequently, we now consider codes that are limited in their applicability to either saturated or unsaturated media, but which introduce some additional flexibility to the methodology.

The first such code is MODFLOW (19), developed by the U.S. Geological Survey. Use of MODFLOW allows very broad flexibility in the types of saturated-zone flow problems that can be modeled, from simple to quite complex. A particle-tracking module, called MODPATH (20), has also been developed. These two codes provide input into a code for analyzing transport, NEFTRAN II (21). NEFTRAN contains a solution to the convective-dispersion model with one-dimensional convection and one-dimensional dispersion, based on a series of stream tubes between the source and the receptor point. The primary incentives for using NEFTRAN are 1) minimization of numerical dispersion for large simulation times, 2) numerical efficiency at very long times, and 3) the ability to model multiple decay chains of any length. Ironically, the approaches used in NEFTRAN that make it efficient for long simulation times also introduce difficulties in its use for low-level waste performance assessment. Unlike the more common finite-element and finite-difference numerical solution approaches, in NEFTRAN numerical dispersion is minimized by maximizing the time step size (within certain constraints). This characteristic of the code is ideal for analyzing integrated contaminant release, which is the original intended use of the code. However, when evaluating peak ground-water concentration for 10 CFR Part 61, it is often necessary to calculate many intermediate time steps to ensure that the analysis does not miss the peak concentration. This issue is particularly important for rapidly varying time-dependent concentrations. In this case, many intermediate time steps may need to be calculated, and this can have the effect of increasing numerical dispersion in NEFTRAN. Some code modifications to NEFTRAN are planned to eliminate these problems. Stream tube volumes can be identified using

MODFLOW and MODPATH. However, caution must be used in defining a stream tube volume for the calculation of concentration, since an overestimation will produce low concentrations and doses.

Source-Term Modeling

Source-term models in the methodology consist of models for the breach of engineered barriers, leaching of radionuclide chemicals into ground water, and transport of radionuclides to the boundary of the disposal unit. Models in the methodology are BLT (22), and the mixing-cell cascade model (16), which is implemented in PAGAN (15). These two approaches each contain advantages and limitations in how they address each individual modeling area. Overall drawbacks to these methods are that neither can model chains in the source, nor can they model gas production.

Since the publication of the methodology, there have been several improvements to source-term models. Sullivan and Suen (23) improved BLT to account for accumulation of concentrations surrounding containers. In addition, a recent extension of the mixing-cell cascade model by Sullivan allows multiple simultaneous release mechanisms. Of greater importance is the development (in progress) of a simplified model for source-term analyses, called DUST (Disposal Unit Source Term) (25). This model is expected to be much easier to use than BLT. Furthermore, unlike BLT, the leaching model results will be useable by alternative transport models.

Since the methodology was developed, there have been developments in the area of concrete modeling. Clifton and Knab (26) assessed the current models for the service life of concrete, and concluded that reasonable assurance of 500 year lifetimes should be possible. Walton *et al.* (27) began developing models for the behavior of partially failed vaults. More recent work by Walton and Seitz (28) has provided guidelines for the design, construction, and operation of vaults. This work included models for evaluating flow and transport under partially failed conditions. Pommersheim and Clifton (29) identified models for evaluating the major degradation processes in concrete to be used in estimating the concrete service life. In addition, Rogers and Associates will soon produce a replacement for BARRIER, called RAESTRICT (30). We do not yet fully know the scope or limitations of this new code.

These improvements still suffer from the limitations of the older models. Limitations on the current models are (1) lack of long-term experience with modern concrete, and (2) lack of an adequate experimental basis for models of flow through either intact or degraded concrete. To build confidence in these models, efforts should be focused on experiments on old (50-100 years old) modern concrete, possibly experiments on ancient (1000-2000 years old) concretes, and comparisons with accelerated tests. It would be very useful to establish an experimental link between accelerated tests and long-term analogs, to provide confidence that the accelerated tests represent long-term behavior (14). Much of the issue of the longevity of concrete is related to quality assurance and quality control during construction rather than parameters that are quantifiable for use in a performance assessment (31). This introduces additional uncertainties into modeling of these structures. Olague *et al.* (14) discuss a possible approach for quantifying this uncertainty.

Another issue that needs to be addressed is the difference between the idealized planned performance of concrete and its performance as emplaced. It is unreasonable to assume that the hydraulic conductivity of a completed vault will be as low as a small laboratory sample of that same concrete. In the concrete itself, differential settlement or stress fractures may cause the concrete permeability to increase during the operational period. In addition, for most designs there will be enhanced degradation of the concrete while the vault is operational, since it will be exposed to the elements above ground. Additionally, the concrete slabs in vaults must be connected by joints, which are made of materials that are not necessarily as long-lived as the concrete itself. For instance, joints may be sealed by metal subject to corrosion or by polymer materials whose longevity is unknown. Less confidence can be placed in the longevity of joint materials than in the longevity of concrete. Another potentially disruptive difference between idealized behavior and actual behavior might be the obstruction of vault drains by sediment or biological clogging, which is a frequent occurrence in sanitary landfills (32).

The modeling approach in the original methodology can be used to model either abrupt or gradual changes in concrete hydraulic permeability. The important issues related to this approach are 1) the hydraulic properties that are appropriate for intact, failed, and partially failed concrete are poorly understood, and 2) it may be desirable to be able to justify gradual failure behavior for the vault. Research efforts should be focused in these areas. The methodology would only be marginally improved by including a model to evaluate the *service life* of concrete vaults, and we do not recommend such models at this time.

Gas Production Modeling

Issues associated with gas generation can be separated into two discrete subjects: generation of gases by the waste, and migration of the gases to the surface. Once the gases reach the surface, they form a release into the atmosphere. Depending on exposure and pathway assumptions, this release at the soil surface may need to be used as an input into an air-transport model for analysis of off-site doses.

Potential gaseous radionuclides in low-level waste include H-3, C-14, and Rn-222. If the disposed waste contains significant amounts of naturally occurring Th-230 or depleted uranium, the potential exists for radon production and transport offsite to be a significant exposure pathway. Although radon's half-life is short, it is the parent of relatively long-lived species (particularly Pb-210), so daughters can potentially be transported in radiologically significant amounts. The short-lived daughters of Rn-222 (Po-218, Pb-214, and Bi-214) can produce significant lung doses from inhalation, since their dose-conversion factors are large. Furthermore, the possibility exists for gaseous transport of radon to plant roots, and then decay of radon to longer lived radionuclides. This could produce a significant dose to man if bioaccumulation of the daughters in edible plant roots occurs. This suggests that there may be an enhanced transportation mechanism to offsite locations for daughters of radon; this transport pathway has been evaluated in the context of naturally occurring radon (33), but studies related to waste disposal sites are unknown to us.

For gas production models, the mechanisms assumed to be occurring are 1) microbial biodegradation of organic materials leading to releases of $^{14}CO_2$ and $^{14}CH_4$, and 2) production of titrated H_2 gas from metal corrosion. The latter mechanism is believed to be of secondary importance, since metallic inventories are not expected to be large. At the present time, we are unaware of any suitable models or experiments for gas generation that would be appropriate for evaluating U.S. low-level waste inventories and disposal conditions. An appropriate experiment would consist of measurements of gas generation from U.S. low-level waste in the physical and chemical conditions likely to be encountered by the waste in a disposal unit. Since most current disposal designs include massive use of concrete, the experiment should be conducted for high pH. Such an experiment may also be appropriate for many arid western sites, which are the only ones for which trench burial is currently being considered (14).

The second aspect of the evolution of gas from the site is its transport from the disposal vault to the ground surface. Subsurface transport of radioactive gases has received considerable attention in the literature since the mid-1970s, owing to increased awareness of the potential for indoor exposure to naturally occurring Rn-222. Consequently, there is a substantial body of empirical and theoretical information available on subsurface transport of gases. This body of literature will be applicable to emission of C-14, H-3, and other possible gas releases from low-level waste as well as to radon emissions. Current thinking about gas exhalation into houses suggests that it is dominated by convective gas flow in the subsurface; measured radon concentrations in houses are too high to be explained by diffusion through the slab (34). The convective flow is the result of barometric pressure changes, which causes transient convective transport of air into and out of the soil. However, it is not clear how the long-term average emission of gas is influenced by barometric pressure oscillations; most studies in the literature have been concerned with the temporal aspects of gas emission (34,35).

Geochemical Modeling

Geochemical models are usually proposed for use in performance assessment as a basis for chemical limitations to transport. These limitations generally take the form of either solubility limitations in the pore fluid or complexation with soil minerals. In order to model these effects, geochemical models are usually developed to identify the chemical speciation, which can then be used to evaluate the processes of interest based on detailed information about the chemical state of the ground water and soil.

Geochemical models are likely to be of greatest use in source-term modeling, since the near-field chemical environment in vaults may be well conditioned compared to the surrounding natural soils. However, even in this well-established environment, geochemical models suffer from a number of drawbacks. Olague *et al.* (14) discuss the lack of an adequate experimental basis for geochemical models.

The constraints on geochemical modeling have not been improved since the methodology was developed. Consequently, there is no impetus to change the models in the methodology to incorporate more sophisticated geochemical models. Instead, it is recommended that site-specific geochemical data should be collected to justify reasonably conservative K_d values for use in performance assessment. Detailed geochemical models may find a role in interpreting site characterization data to justify conservative values for distribution coefficients, K_d, but will probably continue to be excessively complicated for performance assessment.

Surface-Water Transport, Air Transport, and Exposure Modeling

The current methodology uses the surface-water transport models recommended in NRC Regulatory Guide 1.113 (36), the air transport models recommended in NRC Regulatory Guide 1.111 (37), and the exposure pathway models recommended in NRC Regulatory Guide 1.109 (38). All of these models are contained in the GENII computer code (39). For surface water, the GENII model can be used for either a river or a lake, and assumes a constant flow depth, a constant convective velocity, a constant width, a constant lateral dispersion coefficient, a straight channel, and a continuous point discharge of contaminants (6). The air transport model in GENII is a Gaussian plume model that has been adopted as a standard method in regulating both radioactive (38,40) and other (41) airborne species. Additionally, the exposure models contained in GENII account for bioaccumulation in plants, irrigation of various crops, inhalation, ingestion of drinking water and contaminated foods and external exposure (9).

A revised version of GENII has become available, called GENII-S (42). The primary differences between GENII and GENII-S are (1) the capability to perform both deterministic and probabilistic pathway analyses, and (2) an improved user interface. The models in GENII-S are identical to the models in GENII. The user interface implemented in GENII-S is the same one used in PAGAN (15), but has been adapted to accommodate the GENII input and output. GENII-S has attractive features, and the user interface is likely to be more user friendly than the APPRENTICE shell introduced with the original GENII code. GENII-S should therefore be adopted for use in the methodology.

Once the intake of radionuclides for a person have been established based on exposure pathway models, dosimetry models are needed to estimate the effect of this intake on the human body. In the methodology, internationally accepted dosimetry models (43) are used which are based on dose-conversion factors (44). The dosimetry models are implemented in GENII (39).

The International Council on Radiatio Protection (ICRP) has issued updated recommendations on dosimetry (45); these recommendations supersede the recommendations of ICRP 26 (43). Of particular importance in low-level waste performance assessment is a change in organ and tissue weighing factors used in calculating the effective dose (note ICRP 60 effective dose is comparable to ICRP 26 committed effective dose equivalent). The weighing factors have been revised in an attempt to ensure that the effective dose would represent the same level of detriment regardless of the tissue or organ involved.

Despite these changes, the ICRP 26 dose factors are widely accepted, and are still considered to be a standard. Available ICRP 26 guidance (44) does not contain enough information to calculate effective doses according to the ICRP 60 approach. We therefore conclude that these models are currently the best available defensible regulatory dose conversion factors. The ICRP 60 standard should be adopted once guidance is available on values for dose conversion factors.

SUMMARY

The purpose of this paper is to discuss refinements to the existing low-level waste performance assessment methodology. Each modeling area of the methodology has been reviewed, and some additional areas of concern have been discussed. Most importantly, a formal process for conducting a low-level waste performance assessment is advocated. This is an iterative approach that is conservatively biased and is integrated with site characterization activities. The uncertainty analysis approach recommended here consists of analyzing multiple conceptual models, a Monte Carlo analysis with Latin Hypercube sampling for parameter uncertainty, coupled with consideration of all highly likely future states of the site.

The primary recommended modeling changes for the methodology are incorporating NEFTRAN II for analyses of source term and ground-water transport, incorporating MODFLOW to improve the flexibility of the methodology in treating saturated-zone flow, developing a simplified application to replace GENII for many applications, and replacing VAM2D by a code such as VS2DT after adapting the latter code to handle decay chain transport. We believe that NEFTRAN will provide additional flexibility and an intermediate level of complexity that will be useful in some circumstances. All of the codes in the methodology are being integrated into a user-friendly, flexible system.

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