Executive Summary

In the United States, low-level radioactive waste is defined as any radioactive waste arising from operations of the nuclear fuel cycle that is not classified as high-level waste (including spent fuel when it is declared to be waste), transuranic waste, or uranium or thorium mill tailings. Low-level waste is generated in many commercial, defense-related, medical, and research activities. Owing to its definition only by exclusion and its many sources, low-level waste occurs in a wide variety of physical and chemical forms, and it contains a wide range of concentrations of many different radionuclides.

Most low-level waste, except relatively small volumes that contain high concentrations of radionuclides with half-lives on the order of 30 y or longer, is intended for disposal in facilities located on or near the ground surface. Decisions about acceptable near-surface disposals of low-level waste are based in large part on the need to comply with regulatory requirements that have been established by the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE). These regulatory requirements include performance objectives that define allowable radiation exposures of the public at future times due to releases of radionuclides to the environment.

In order to determine whether a particular facility complies with regulatory performance objectives for long-term protection of the public, a **performance assessment** of the facility must be conducted. As used in this Report:

> Performance assessment is an iterative process involving site-specific, prospective modeling evaluations of the post-closure time phase of near-surface disposal systems for low-level waste with two primary objectives:
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> - to determine whether reasonable assurance of compliance with quantitative performance objectives can be demonstrated; and
> - to identify critical data, facility design, and model development needs for defensible and cost-effective licensing decisions and to develop and maintain operating limits (*i.e.*, waste acceptance criteria).

This definition emphasizes that performance assessment focuses primarily on a decision about compliance with performance objectives, rather than the much more difficult problem of predicting actual radiological impacts on the public at far future times.

The purpose of this Report is provide a review of concepts underlying performance assessments of near-surface disposal facilities for low-level waste and approaches to conducting such assessments. This review includes discussions on the nature and scope of performance assessment, accepted approaches to conducting all aspects of a performance assessment, and unresolved issues in conducting performance assessments and applying the results. Challenges in conducting and defending performance assessments at specific sites also are emphasized.

An understanding of general principles of performance assessment is important, because such understanding can lead to an efficient process and defensible product and can reduce the potential for misinterpretation of results. General principles of performance assessment are summarized as follows:

- Performance assessment should be an iterative, flexible process of integrating modeling, data collection, and design activities in a manner that identifies those aspects of engineered and natural barriers in a disposal system of importance to a decision about compliance with regulatory performance objectives. The performance assessment process is important during all time phases of a facility from site selection and facility design through operations and postclosure monitoring and surveillance.
- Performance assessment is a process that is intended to provide *reasonable assurance* of compliance with performance objectives; absolute assurance of compliance generally is not attainable by any means unless disposal of only very small quantities of radionuclides is allowed.
- Since there is substantial uncertainty in models and important parameters used in performance assessment and some physical, chemical, and biological processes that affect the long-term performance of a disposal system may not be well understood, use of subjective scientific judgment is an essential aspect of performance assessment. Therefore, a variety of results that investigate the consequences of different plausible assumptions should be presented, rather than a single projected outcome.
- An integration and interpretation of assumptions and results, in which conceptual models of the performance of a disposal

> system and their bases and the results of calculations are presented in a manner that reflects the many judgments involved and the importance of different aspects of an assessment to a demonstration of compliance with regulatory performance objectives, is a critical aspect of performance assessment.

Quantitative performance objectives for near-surface disposal of low-level waste in NRC and DOE regulations are expressed in terms of limits on annual dose to members of the public, either equivalent dose to specific organs or tissues or effective dose equivalent. Therefore, projections of maximum concentrations of radionuclides in the environment at assumed locations of exposure are required. Although regulations are well established, a number of issues regarding performance objectives and their implementation are not yet fully resolved or are controversial. These include (1) the time period for compliance and the weight, if any, that should be given to projections of performance beyond the compliance period in determining acceptable disposals, (2) whether projected doses due to radon are included in performance objectives, which is potentially important in determining acceptable disposals of waste that contains radium, thorium, or uranium, (3) whether performance objectives should include a separate requirement for protection of groundwater resources in accordance with drinking water standards, which is important when drinking water standards would be more restrictive in determining allowable releases of many radionuclides than the existing performance objectives that apply to all exposure pathways combined, and (4) interpretation of performance objectives for compliance purposes—*i.e.*, how highly uncertain results of performance assessments should be compared with fixed performance objectives in judging compliance.

At most sites, movement of water is considered to be the most important means by which radionuclides may be released from a disposal facility and transported to locations where exposures of the public could occur. Even for the simplest types of near-surface facilities (*e.g.*, an unlined trench with backfill and cap consisting of earthen materials), performance assessment requires an integration of results of a number of different types of models to provide an overall description of the performance of a disposal system. The usual approach to performance assessment is to model various components of the system separately and then link the components in a sequential fashion, with appropriate boundary and continuity conditions, to describe overall system performance. The different components that generally must be considered in a performance assessment are the following:

- an analysis of **cover performance and infiltration**, the primary purpose of which is to estimate the flux of water (*i.e.*, incident precipitation) that infiltrates through a natural or engineered cover system to locations of disposed waste or an engineered barrier (*e.g.*, a concrete structure) above the waste; the performance of a cover system in inhibiting atmospheric releases of radionuclides in gaseous form also can be important at some sites and for some wastes;
- an analysis of the performance of **concrete barriers** (*e.g.*, vaults, modular canisters, or bunkers) that are used in many disposal facilities to enhance containment of low-level waste by (1) providing structural support for an earthen or engineered cover system, (2) delaying and inhibiting inflow of water to locations of disposed waste, (3) supplying additional adsorbing materials to retard movement of radionuclides into the surrounding environment, and (4) delaying and inhibiting release of radionuclides in leachate from a facility;
- an analysis of the **source term**, the purpose of which is to estimate the rate of release of radionuclides from a disposal facility into the surrounding environment, either the vadose zone when releases are in liquid form or the atmosphere when releases are in gaseous form, by considering rates of release from waste forms and waste containers, transport within a disposal facility, and transport through any engineered barriers used in constructing the facility;
- an analysis of **flow and transport in the unsaturated (vadose) zone**, which uses results of source-term modeling of liquid releases as input and provides estimates of releases into groundwater (zone of saturation);
- an analysis of **flow and transport in groundwater (zone of saturation)**, which uses results of modeling of flow and transport in the vadose zone, as well as any additional direct recharge to an aquifer that may occur due to runoff from a cover, as input and provides estimates of concentrations of radionuclides in groundwater at assumed locations of exposure; an analysis of **flow and transport in surface water** also may be required when groundwater into which releases occur discharges to the surface at locations close to a facility;
- an analysis of **atmospheric transport**, which uses results of source-term modeling of gaseous releases or other means of transport of buried waste to the ground surface and release to the atmosphere as input and provides estimates

of airborne concentrations of radionuclides at assumed locations of exposure;
- an analysis of **biotic transport**, which considers actions of plants and animals that could affect transport of buried waste to assumed locations of exposure; biotic transport is not often considered explicitly in performance assessment, but it can serve to enhance release and transport of radionuclides and can be important at some sites; and
- an analysis of **exposure pathways and radiological impacts**, which uses results of environmental transport models (*i.e.*, groundwater or surface water flow and transport, atmospheric transport, or biotic transport models) that estimate concentrations of radionuclides in environmental media at assumed locations of exposure as input and provides estimates of transport through various exposure pathways to human receptors and the resulting radiation doses.

Atmospheric and biotic transport often are considered to be unimportant compared with transport in water. However, these processes can be important in some environments and for some facility designs, and their importance generally should be evaluated in site-specific analyses.

NRC and DOE regulations also require that near-surface disposal facilities provide protection of hypothetical inadvertent intruders who are assumed to come onto a disposal site after loss of institutional control and access disposed waste by such means as excavating to construct a foundation for a home or drilling. Protection of inadvertent intruders at sites licensed under NRC regulations is provided by the NRC's waste classification system, which specifies limits on concentrations of radionuclides in Class-A, -B, and -C waste and technical requirements on disposal of waste in each class. At DOE sites, a site-specific assessment of potential impacts on inadvertent intruders is required for the purpose of establishing limits on concentrations of radionuclides; these limits can vary greatly depending on site conditions and the design of a facility. Under either regulations, compliance with a requirement to protect inadvertent intruders is based on analyses of potential radiological impacts in assumed intrusion scenarios. Standard scenarios that are often used are reviewed in this Report. Given that there are separate requirements to protect members of the public and inadvertent intruders, determinations of acceptable near-surface disposals of low-level waste essentially involve achieving a balance between acceptable releases of radionuclides beyond the site boundary and acceptable residual concentrations in a disposal facility after loss of institutional control. If excavation into waste and residence on a disposal site in a homesteader scenario are considered to be credible occurrences, criteria that define adequate protection of inadvertent intruders usually are more restrictive in determining acceptable disposals than performance objectives for protection of the public or the environment. Therefore, selection of credible intrusion scenarios can be very important in determining acceptable disposals in near-surface facilities.

Performance assessments generally must consider uncertainties in models and parameter values, which result in uncertainty in results of modeling (*e.g.*, projected doses to the public), and the sensitivity of model outputs to changes in assumptions and variations in parameters. Since the primary purpose of performance assessment is to provide a demonstration of compliance with regulatory performance objectives, a particular kind of uncertainty and sensitivity analysis, which is termed **importance analysis**, is emphasized in this Report. Importance analysis is an integration and interpretation of results obtained from the performance assessment process for the purpose of identifying assumptions and parameters which, when changed within credible bounds, can affect a decision about regulatory compliance. This type of analysis, which focuses on uncertainties and sensitivities that are important to a decision about compliance with performance objectives, is different from more traditional uncertainty and sensitivity analyses, which are concerned with representing uncertainty in the actual behavior of a disposal system and outcomes of waste disposal. An understanding of the distinction between importance analysis and traditional sensitivity and uncertainty analysis is important in conducting performance assessments efficiently and defending the results.

Models of varying degrees of sophistication and complexity have been developed for all components of a performance assessment. However, detailed modeling of all aspects of the performance of a disposal system is beyond current capabilities and, indeed, is not required to achieve defensible results and robust decisions about the acceptability of waste disposals. Since there are a large number of radionuclides in low-level waste and a large number of potential pathways for transport and exposure, simple screening analyses to select for further analysis only those radionuclides and pathways that contribute significantly to projected doses to the public are an important initial step in making a performance assessment tractable. Once radionuclides and pathways are selected for further analysis, many stylized and simplifying assumptions normally are used in performance assessment in the interest of expediency. Examples of such assumptions include the following:

- The potential importance of future climate change on infiltration and release and transport in water either is not considered or is modeled by assuming an abrupt change to an expected climate at some future time.
- Infiltration through natural or engineered cover systems usually is modeled by assuming steady-state conditions, and transients that might occur as a result of episodic precipitation events are ignored. Failure of a cover system usually is modeled by assuming an instantaneous change or a series of instantaneous changes to natural conditions at some future time.
- Degradation or failure of engineered barriers, either physical or chemical, usually is modeled by assuming an instantaneous change from an initial condition to a failed state at some future time or a constant rate of failure.
- When there are highly heterogeneous distributions of radionuclides and a multiplicity of waste forms in a disposal facility, source terms usually are modeled by averaging radionuclide distributions over individual disposal units and assuming no more than a few idealized representations of waste forms.
- The physical structure of unsaturated and saturated geologic media and their geochemical properties usually are assumed to be homogeneous and isotropic.
- A graded approach to modeling flow and transport in the unsaturated (vadose) zone may be taken in which all or parts of the unsaturated zone are ignored (*e.g.*, releases from a disposal facility are assumed to directly enter an underlying aquifer) or, less conservatively, a unit-gradient model that assumes steady-state flow and a flow rate equal to the infiltration rate is used.
- The interface between models of flow in the vadose and saturated zones often is represented by simple boundary conditions (*e.g.*, zero pressure head).
- A linear sorption isotherm, described by the equilibrium solid/solution distribution coefficient (K_d), usually is assumed to represent all geochemical effects on transport in the disposal facility following release from a waste form and waste package and transport in the vadose and saturated zones.
- All physical and chemical processes that affect release and transport of radionuclides often are assumed to be independent of radionuclide concentrations in waste, and the performance of the disposal system (*e.g.*, projected dose to the public) is assumed to depend linearly on those concentrations.

Challenges in conducting performance assessments and defending the results in a regulatory setting, which is tantamount to defending important assumptions, increase as the quantities of radionuclides that are intended for disposal in a facility increase and compliance with performance objectives cannot be demonstrated by using clearly conservative (pessimistic) models for highly uncertain components of performance. The lack of relevant site-specific data or data over time and spatial scales of importance is a frequent concern. Some of the challenges in modeling the performance of a disposal system when water is the medium in which releases are assumed to occur and a high level of performance of natural and engineered barriers is required to demonstrate compliance with performance objectives are summarized as follows:

- *Cover performance and infiltration*: It can be difficult to justify that an engineered cover will perform as designed and constructed to control infiltration over time periods much beyond the period of institutional control.
- *Concrete barriers*: There is little relevant data to predict the structural integrity and load-bearing capabilities of concrete over long time periods, so it is difficult to justify assumptions about structural integrity at times beyond several hundred years. Assumptions about infiltration through degraded concrete structures, including the relative importance of flow in fractures and pores, can be an important issue.
- *Source term*: Inventories of radionuclides that often are expected to be the most important in releases to groundwater (*e.g.*, ^{14}C, ^{99}Tc, and ^{129}I) can be difficult to estimate. Modeling of releases can be challenging when radionuclide distributions are heterogenous and several waste forms are used. Although grout provides a homogeneous waste form for liquid wastes, modeling of long-term changes in hydrologic and geochemical properties of grout waste forms can be difficult when there are little relevant data and judgment must be relied on.
- *Unsaturated (vadose) zone flow and transport*: Modeling at a detailed level is data-intensive and difficult to defend at specific sites owing to the complex, nonlinear relationships between moisture content, pressure (suction) head, and hydraulic conductivity and their dependence on soil type. A defensible conceptual model of flow and transport in unsaturated fractured rock is not yet available.

- *Saturated zone flow and transport*: A groundwater velocity field is not directly measurable but must be generated using a model that is based on data on hydraulic head from monitoring wells and data on pump or core hydraulic conductivity tests. A velocity field so generated is non-unique, and multiple interpretations of data, with different effects on performance, may be reasonable at any site. Other issues of potential concern in modeling saturated zone flow include assumptions about boundary conditions, use of transient data to model steady-state conditions, the spatial scale and heterogeneity of a velocity field, modeling of flow in fractured rock, and the applicability (scaling) of laboratory data to field conditions. Issues in modeling transport include the simplistic nature of the K_d concept, justification of assumed K_d values at specific sites, treatments of diffusion and dispersion, and a lack of site-specific data on dispersivities.

In contrast, modeling of atmospheric transport and exposure pathways and radiological impacts rarely is difficult or controversial, in part because the relevant processes are well understood and there are extensive studies to validate models normally used in performance assessments.

A central issue that must be confronted in all performance assessments is whether simple and clearly conservative models should be used in demonstrating compliance with performance objectives or whether more complex and rigorous modeling should be undertaken in an effort to provide more realistic projections of outcomes at times far into the future. Either approach may be desirable for many reasons, and both have their difficulties. The point of view taken in this Report is that an appropriate balance between conservatism and more realistic approaches to performance assessment is largely a matter of judgment that should be applied on a site-specific basis. All performance assessments should attempt to incorporate some degree of realism to demonstrate an appropriate level of understanding of the long-term performance of disposal systems. The goal should be to provide a cost-effective and defensible assessment that is commensurate with the hazards posed by wastes that are intended for disposal at a specific site. At some sites with highly desirable characteristics, use of simple and conservative models for some aspects of system performance may not affect a decision about regulatory compliance. At other sites, however, efforts at more realistic modeling may be required. At any site, it is important to recognize that performance assessment is conducted to inform decisions about the acceptability of waste disposals, and that it is not necessary to obtain realistic projections of outcomes to render such decisions in a defensible manner. Although performance assessment involves a significant amount of subjective scientific judgment and there are important limitations in regard to predicting actual outcomes, these factors do not compromise the essential role of performance assessment in regulatory decision making.