ANALYSIS OF DEPLETED URANIUM DISPOSAL

OVERVIEW:

A screening model has been developed by staff of the performance assessment branch in the Division of Waste Management and Environmental Protection to evaluate the risk and uncertainties of depleted uranium (DU) disposal as low-level waste (LLW) with near-surface disposal at a generic site. The model was developed to understand the impacts of key variables on the risks from disposing of DU in near-surface disposal, such that staff could respond to Commission direction to consider whether the quantities of DU in the waste stream from uranium enrichment facilities warrant amending the waste classification tables in 10 CFR Part 61 (Part 61). The model was developed to evaluate the radiological risk to potential future residents and intruders (acute or chronic exposures) near or on the land overlying a hypothetical disposal facility for the large quantities of DU anticipated to be disposed of as a result of fuel enrichment facility operations. The model was designed to provide the user flexibility in evaluating different waste types and forms, disposal configurations, performance periods, institutional control periods, pathways, and scenarios.

The model was constructed with the dynamic simulation software package GoldSim®, developed by GoldSim Technology Group of Issaquah, WA. Goldsim is a Monte Carlo simulation software solution for dynamically modeling complex systems in business, engineering and science. GoldSim is used for decision and risk analysis by simulating future performance while quantitatively representing the uncertainty and risks inherent in all complex systems. GoldSim has been used by U.S. Nuclear Regulatory Commission (NRC) staff to risk-inform reviews of U.S. Department of Energy (DOE) performance assessments (Esh, 2002; Esh, 2006). GoldSim is used by over 30 organizations in the field of radioactive waste management. A component or modular approach can be used in GoldSim to build a performance assessment model, which is the approach used in this analysis. Main submodels include inventory, source term, infiltration, radon, groundwater transport, and biosphere. Submodels use deterministic and probabilistic input values or distributions.

The model was used to understand the impacts of key variables on the risks from disposing of DU in near-surface disposal. Key variables evaluated were: disposal configurations, performance periods, institutional control periods, waste forms, site conditions, pathways, and scenarios. Calculations were performed probabilistically to represent the impact of variability and uncertainty on the results. The analysis methodology in the current assessment was consistent with the technical analysis methodology used for the development of the environmental impact statements supporting Part 61. This approach allowed constraints to be identified for the safe disposal of large quantities of DU in near-surface disposal. Because there were a wide range of variables considered, summary conclusions are not absolute; *a site-specific analysis may demonstrate compliance with the performance objectives when the summary conclusions found below indicate otherwise*. However, the properties and characteristics of DU present constraints on approaches for disposal. The summary conclusions provide the technical framework for policy decisions. The main technical observations are:

- Depleted uranium has some characteristics that are dissimilar from commercial LLW.
    - A large percentage of the activity is associated with very long-lived radionuclides.

  - Radioactive decay results in increasing hazard with time until after 1 million years, as a result of increasing concentrations (and higher mobility) of decay products.
  - In-growth of significant quantities of a daughter in gaseous form (^{222}Rn)
- Estimated risks are sensitive to the performance period.
- Estimated risk from radon is sensitive to the disposal depth.
- Radon fluxes to the environment are very sensitive to the long-term moisture state of the system.
- Large uncertainties (and little available data) associated with some transfer factors for uranium daughter products.
- Estimated disposal facility performance is strongly dependent on site-specific hydrologic and geochemical conditions.
- Radon is limiting at arid sites and for shallow disposal.
- The groundwater pathway is limiting at humid sites.
- Grouting of the waste may improve the likelihood of an arid site meeting the performance objectives with respect to radon; however, grout may enhance the mobility of uranium in the groundwater pathway after the grout degrades.

The summary conclusions from the technical analysis are:

- Near-surface disposal (i.e., less than 30 meters [m], as defined in Part 61) may be appropriate for large quantities of DU under certain conditions. However, unfavorable site conditions can result in the performance objectives not being met. Examples of unfavorable conditions include shallow disposal (< 3 m depth) and humid sites with a potable groundwater pathway.
- Because of the in-growth of radon and other daughter products, periods of performance of 1,000 years or less result in a significant truncation of estimated risk.
- Shallow disposal (< 3m deep) is likely to not be appropriate for large quantities of DU, regardless of site conditions. Shallow disposal may be possible if robust intruder barriers, excluding the possible excavation of DU, and a robust radon barrier that can effectively limit radon fluxes over the period of performance are installed, and their performance is justified. Small quantities (1 – 10 metric tons) could be disposed of at shallow depths.
- Depleted uranium can be disposed of under arid conditions and meet the Part 61 performance objectives for 1,000 to 1 million year performance periods, if the waste disposal depth is large, or robust barriers are in place to mitigate radon.
- Disposal under humid conditions with viable water pathways is probably not appropriate for large quantities of DU.

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Acronyms

ACNW	Advisory Committee on Nuclear Waste
AEA	Atomic Energy Act
CFR	Code of Federal Regulations
DEIS	Draft Environmental Impact Statement
DOE	Department of Energy
DU	Depleted uranium
EPA	Environmental Protection Agency
FEIS	Final Environmental Impact Statement
HLW	High-Level Waste
ICRP	International Committee on Radiation Protection
LLW	Low-Level Waste
LLRW	Low-Level Radioactive Waste
LLRWPAA	Low-Level Radioactive Waste Policy Act Amendments
NAS	National Academy of Sciences
NRC	Nuclear Regulatory Commission
TEDE	Total Effective Dose Equivalent

INTRODUCTION

The NRC staff is conducting a technical analysis to assess the potential impacts of disposal of large quantities of DU in a generic near-surface disposal facility and to determine if current low-level radioactive waste (LLRW) classification criteria warrant modification for large quantities of DU. Staff of the performance assessment branch in the Division of Waste Management and Environmental Protection developed a screening model to evaluate the risk and uncertainties associated with the disposal of DU in near-surface disposal. The model was developed to understand the impacts of key variables on the risks from disposing of DU as LLW, such that the staff could respond to Commission direction to consider whether the quantities of DU in the waste stream from uranium enrichment facilities warrant amending the waste classification tables in Part 61.

The model was developed to evaluate the radiological risk to potential future residents and intruders (acute or chronic exposures) near or on the land overlying a hypothetical disposal facility for DU. The model was designed to provide the user with flexibility to evaluate different waste forms, disposal configurations, performance periods, institutional control periods, pathways, and scenarios. The impact of these variables on projected radiological risk can be significant. Therefore, the model was developed as a first-order assessment tool to risk-inform decision making. Refinement of the model would be necessary if it was to be used for licensing decisions, and rigorous validation would be needed. Because site-specific waste management decisions or other variables can strongly influence whether performance objectives can be met, care should be taken not to take the model results out of the analysis context.

The model was constructed with the dynamic simulation software package GoldSim®, developed by GoldSim Technology Group of Issaquah, WA. Goldsim is a Monte Carlo simulation software solution for dynamically modeling complex systems in business, engineering, and science. GoldSim is used for decision and risk analysis, by simulating future performance while quantitatively representing the uncertainty and risks inherent in all complex systems. GoldSim has been used by NRC staff to risk-inform reviews of DOE performance assessments (Esh, 2002; Esh, 2006). GoldSim is used by over 30 organizations in the field of radioactive waste management.

This report is not intended to provide full documentation of the technical analysis performed to develop the risk insights associated with DU. The report is intended to provide a summary of the analysis and resultant risk insights developed by the staff.

PROBLEM CONTEXT

The NRC LLRW regulatory program ensures the continued safe and secure LLRW disposal under the Atomic Energy Act (AEA) of 1954 and the Low-Level Radioactive Waste Policy Act Amendments (LLRWPAA) of 1985. A primary goal of the LLRWPAA is to ensure that disposal capacity would be available for all classes of LLRW generated by AEA licensees. Criteria for determining the classification of LLRW are specified in Part 61 of Title 10 of the Code of Federal Regulations (CFR). The original development of Part 61 did not explicitly consider a waste stream involving the large amounts of DU that has ensued from the operation of a commercial uranium enrichment facility (NRC, 1981). Therefore, the Commission directed the staff to consider whether the quantities of DU in the waste stream from uranium enrichment facilities warrant amending the waste classification tables in Part 61 (NRC, 2005). The nature of the radiological hazards associated with DU presents challenges to the estimation of long-term effects from its disposal – namely that its radiological hazard gradually increases due to the in-growth of decay products, eventually peaking after 1 million years, rather than decreasing significantly over a few hundred years like that of typical LLW.

Characteristics of DU

Depleted uranium can have a variety of chemical and physical forms dependent on the enrichment process used. Depleted uranium is produced in the enrichment process as a waste product or byproduct. The source term results from the fact that the enrichment process concentrates both the ^{235}U and ^{234}U in the product, and therefore, these radionuclides are depleted in the waste or byproduct. Metallic DU contains approximately 99.75 percent ^{238}U, 0.25 percent ^{235}U, and 0.002 percent ^{234}U (Kozak, 1992). Depleted uranium oxide contains approximately 85 percent uranium by mass. In comparison, a low-grade uranium ore common in the United States may contain 0.1 percent uranium by mass. The most prevalent forms of DU for disposal resulting from fuel cycle activities are depleted uranium hexafluoride (UF_6) and depleted uranium oxide (UO_2 or U_3O_8), which results from deconversion of fluoride forms. Uranium oxides include UO_2, U_3O_8, and uranium trioxide. Both UO_2 and U_3O_8 are solids that are significantly more stable than UF_6 over common disposal conditions, making the oxide forms more suitable for long-term storage or disposal. Uranium hexafluoride reacts with water to form corrosive hydrogen fluoride (HF).

Depleted uranium contains three principal radionuclides after production: ^{238}U, ^{235}U, ^{234}U. Over time, the parent radionuclides decay through the uranium series decay chains producing daughter radionuclides. In natural ores, the daughter radionuclides are generally in secular equilibrium with the parent radionuclides. For mill tailings, a significant portion of the total activity at the time of disposal is associated with radium, therefore disposal or management decisions can focus on the radiological inventory at the time of disposal. For example, a barrier to attenuate the emanation of radon from mill tailings can be designed based on the concentration of the material at the time of disposal. On the other hand, DU is essentially depleted in the daughter radionuclides but concentrated (compared to natural ore or mill tailings) in the parent radionuclides. Over long periods of time, the uranium parent radionuclides have the potential to produce quantities of daughter radionuclides significantly in excess of natural ores or mill tailings because the DU source has much higher concentrations of uranium. For example, mill tailings commonly have from 0.004 to 0.02 wt percent U_3O_8, 26 to 400 pCi/g ^{226}Ra, and 70 to 600 pCi/g ^{230}Th at the time of disposal (Robinson, 2004). Depleted uranium (in oxide form) would have approximately 99.9 percent uranium oxide at the time of disposal and greater than 300,000 pCi/g ^{226}Ra and ^{230}Th approximately 1 million years after disposal (values cited were calculated with a simple decay/in-growth calculation). Because the daughter radionuclides are different elements, they have different mobility in the environment than the parent radionuclides and in some cases are significantly more mobile (e.g., radon).

Figure 1 provides the ratio of the activity of DU at various times to its initial activity. For comparison, a similar ratio for a commercial LLW facility is provided based on data from Barnwell, South Carolina (Chem-Nuclear Systems, 1995). Whereas the activity in a commercial LLW facility decreases to a few percent of the initial value over a few hundred years, the activity in a facility for DU would be expected to remain relatively constant initially, but begin increasing

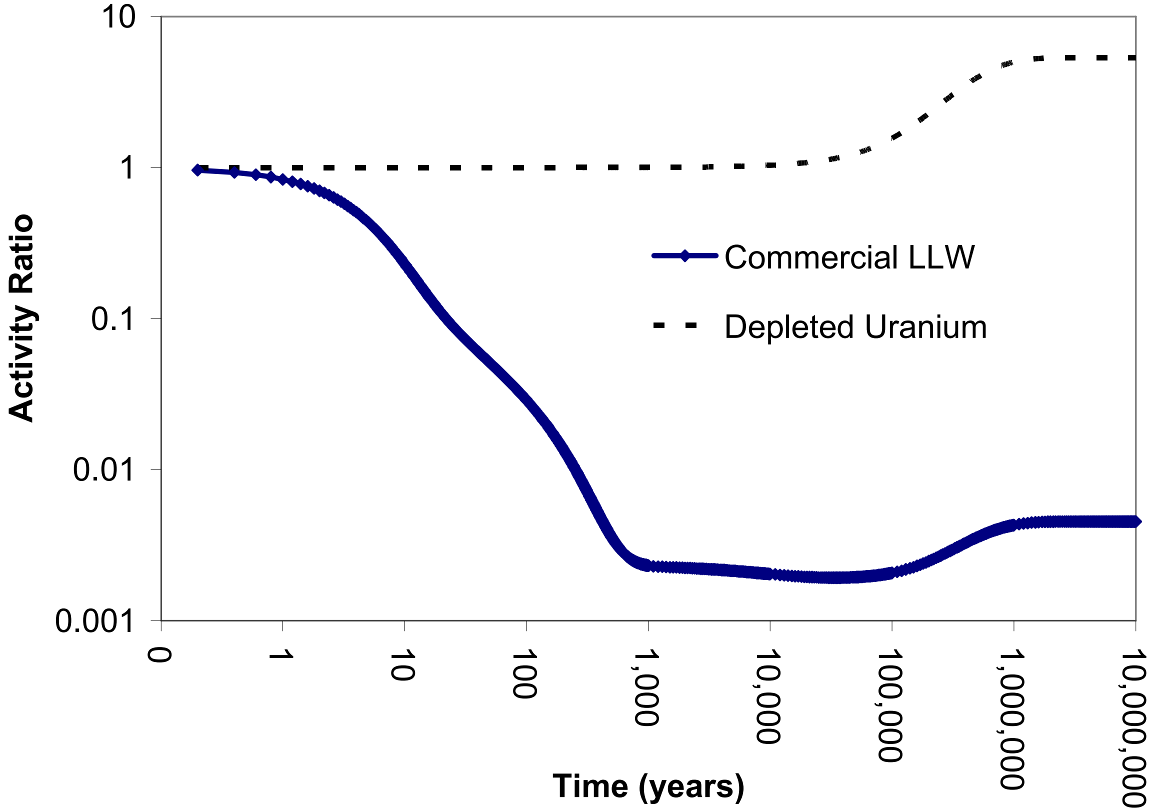


Figure 1 Activity Ratios of DU and a Commercial LLW Facility. The activity ratios are defined as the initial activity to the activity at various points in time.

at around 1,000 years. Peak activity, assuming no release from the source, would not be attained until after 1 million years after disposal. The ratio for DU shown in Figure 1 is determined by the number of daughter radionuclides represented in the decay chain, because the daughter radionuclides are in secular equilibrium with the long-lived parents for long periods of time. In addition, the activity of some risk significant radionuclides (e.g., ^{222}Rn, ^{210}Pb) increase by a much more significant amount than the overall activity. The activity of ^{222}Rn and ^{210}Pb in particular increase by more than a factor of 1,000 between 1,000 years to 1 million years after disposal. Because different elements can have different mobility and radiotoxicity, total activity cannot be directly translated to risk (dose). As a result of these characteristics of the source term, assessment of the risk of DU disposal in the near-surface requires an evaluation of a number of different features, events, and processes over timeframes that could be substantial.

Past Regulatory Approaches to LLW Analysis

The Draft Environmental Impact Statement (DEIS) (NUREG-0782), the Final Environmental Impact Statement (FEIS) (NUREG-0945), and an update to the impact analysis methodology (NUREG/CR-4370) for Part 61 provide a description of the analysis approach for evaluation of near-surface disposal of commercial LLW. These references provide a full description of the analysis approach. This section provides a summary of key aspects and assumptions for the analysis in order to provide context for the current problem.

The analysis to support development of Part 61 considered different periods of institutional control (NRC, 1981). The final regulations in 10 CFR 61.59(b) specify that institutional controls may not be relied upon for more than 100 years. At the time of development of Part 61, it was envisioned that LLW in a disposal facility would decay, in a maximum of 500 years, to activity levels that would not pose a significant risk to an inadvertent intruder, and that there would not be significant quantities of long-lived isotopes which would pose unacceptable long-term risks to the public from releases from the facility. In developing Part 61, NRC considered longer periods of institutional control in the DEIS (NRC, 1981). Assumptions about the persistence of institutional controls in the international community were considered and a series of public meetings were conducted to get input from stakeholders. The consensus among the stakeholders was that it is not appropriate to assume institutional controls will last for more than a few hundred years. The resultant regulatory framework for commercial LLW disposal assumes material that does require institutional control for much longer than 100 years to demonstrate compliance with the performance objectives would generally be determined to not be suitable for near-surface disposal as LLW. The regulatory philosophy is that the engineered and natural system should afford protection to the public, without total reliance on institutional control of the site, because of the relatively large uncertainty associated with predicting societal systems. The institutional controls allow monitoring and maintenance of the disposal facility to be completed and also restrict access to a disposal facility after closure (NRC, 1981).

The analysis for development of Part 61 applied the following assumptions with respect to receptors and eventual use of the disposal site. After the period of active institutional control ended (as discussed above), the public receptor was assumed to engage in residential, agricultural, or other activities at the boundary of the disposal site. These assumed activities were consistent with current regional practices. The disposal site included a buffer zone around the disposal area, where the disposal area circumscribed the disposal units (NRC, 1982). An appropriate buffer zone was expected to extend approximately 100 m (330 feet [ft]) from the disposal area, although buffer zones up to 1,000 m (3,300 ft) were considered. A receptor engaging in activities on the disposal site, rather than outside the buffer zone, was regarded as the inadvertent intruder. A receptor engaging in activities at the edge of the buffer zone was regarded as a member of the public. Figure 2 provides a schematic representation of the concepts considered.

The Part 61 impacts analysis was generic in nature and focused toward helping to establish generic criteria for LLW management and disposal, including developing requirements for waste classification (NRC, 1981). A fairly large number of variables were considered in the analysis, including, but not limited to: waste form and processing, disposal environment, facility design, control, and technical indices for aspects such as leachability, dispersibility, stability, and chemical content. Impacts were assessed for offsite members of the general public as well as onsite acute and chronic scenarios resulting from exposure to or disruption of the waste. Inadvertent intrusion was assumed to occur following a breakdown of institutional controls. The intruder was assumed to excavate and construct a residence on the disposal site (intruder-construction), or occupy a dwelling located on the disposal site (intruder-agriculture) and ingest food grown in contaminated soil (NRC, 1981). The intruder-agriculture scenario was assumed to be possible only if the waste had degraded to an unrecognizable form. Exposure to radionuclides through inhalation of contaminated soil and air, direct radiation, and ingestion of contaminated food and water were considered. Additional exposed waste scenarios were considered as well as other potential exposure pathways. The intruder-agriculture scenario,

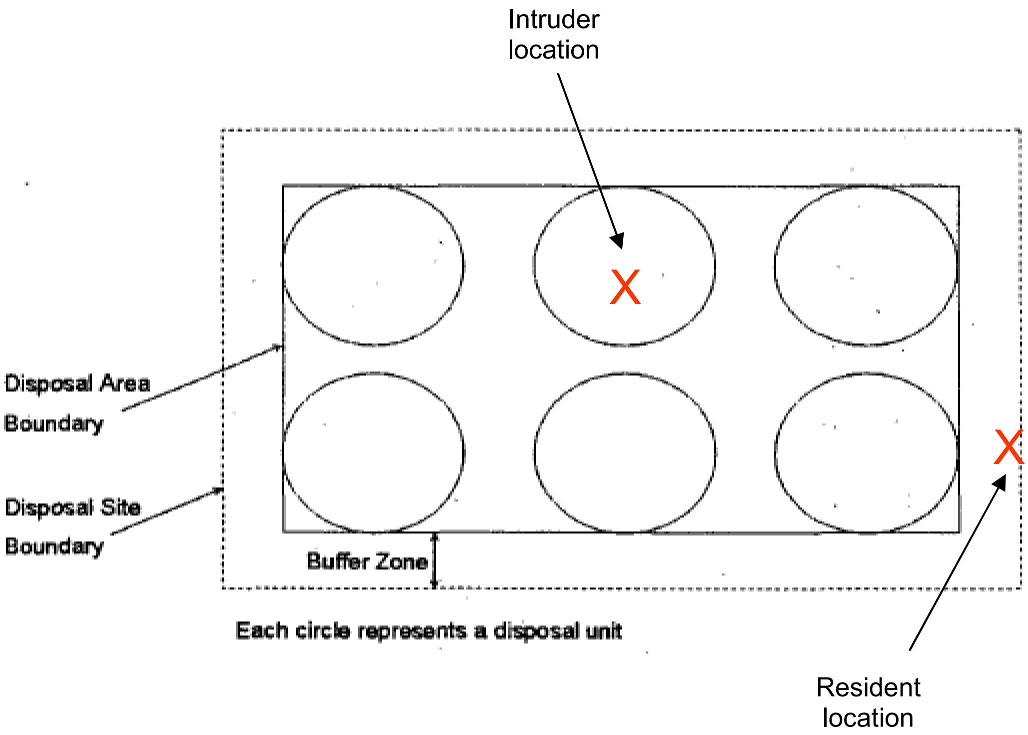


Figure 2 Geometric Relationship of the Disposal Units, Disposal Area, and Buffer Zone of a Disposal Site. Adapted from the Final Environmental Impact Statement for Part 61 (NRC, 1982).

along with a 500 millirem (mrem) dose value, was used to develop the waste classification tables found at 10 CFR 61.55. Requirements for a specific intruder scenario or dose value are not found in Part 61. The use of a higher dose value for the inadvertent intruder analysis (500 mrem), compared to the value specified in 10 CFR 61.41 for the general public (25 mrem/yr), implies that the loss of institutional control by a state or federal agency was believed to be unlikely, if a similar level of protection was being afforded to a member of the public whether they were an intruder or resident receptor. The approach to developing the waste classification system was believed to provide protection of public health and safety under a variety of conditions. However, it was also recognized that unique characteristics of waste, disposal sites, and methods of disposal may lead to alternative requirements for waste classification.

The update of the Part 61 impacts analysis methodology explicitly addressed the effects of radon gas generation (NRC, 1986), which is important for disposal of DU in the near-surface. Radon was recognized to be generated in some waste streams, in which case the in-growth of radon gas in buildings was expected to be included in the intruder-agriculture scenario. The impacts analysis update provided approaches to calculate radon doses, and stated that the doses should be added to other impacts calculated for the intruder-agriculture scenario. However, the DEIS and FEIS did not envision large quantities of material that could generate radon would be disposed of as LLW. The Part 61 DEIS assumed 17 Curies (Ci) of ^{238}U and 3 Ci of ^{235}U would be disposed of in 1 million m^3 of waste over a 20-year generic LLW site operating life (NRC, 1981). The performance objectives in Subpart C of Part 61 do not provide explicit requirements for radon. Radon is discussed in NUREG-1573, *A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities: Recommendations of NRC's Performance Assessment Working Group,* as being included as part of the assessment of gaseous releases in LLW disposal (NRC, 2000). The U.S. Environmental Protection Agency (EPA) standards for uranium mill tailings (40 CFR 192) provide a ^{222}Rn release rate limit of 20 picocuries (pCi)/m^2-s from the cover over the tailings and a ^{222}Rn concentration in free air (outside the site, above background) of 0.5 pCi/L. The DOE takes a similar approach to managing radon from disposal facilities, through specification of a 20 pCi/m^2-s flux limit. For comparison, the mean value for atmospheric radon in the United States is approximately 0.25 pCi/L. Studies of indoor radon levels indicate an average concentration of from 1.5 to 4.2 pCi/L (Alter and Oswald, 1987; Nero et al, 1986). Daily intake of radon is generally much more significant from indoor exposure than from outdoor exposure. Indoor radon concentrations are higher because the flow rate of clean air (i.e., the exchange rate) is much lower than outdoors, and other factors. Daily intake of radon indoors is as much as ten times higher than outdoors (Cothern et al., 1986). The flux limit standard of 20 pCi/m^2-s would generally result in inhalation doses to a hypothetical resident next to the disposal facility on the same order as the 10 CFR 61.41 dose limit of 25 mrem/yr. However, the translation of a flux rate to dose is dependent on a number of site-specific and receptor scenario variables.

Period of Performance

The staff has reviewed various approaches for the period of performance under several NRC regulations. The following discussion summarizes current NRC regulatory approaches to the period of performance in waste management.

A value for the performance period is not provided in Part 61, in part due to the site-specific and source-specific influence on the timing of projected risk from a LLW facility. A performance period of 10,000 years was included in the DEIS for Part 61 (NUREG-0782). The recommended performance period by the performance assessment working group for a typical commercial LLW facility is 10,000 years (NRC, 2000). This performance period is considered to be sufficiently long to capture the risk from the short-lived radionuclides, which comprise the bulk of the activity disposed, as well as the peaks from the more mobile long-lived radionuclides, which tend to bound the potential doses at longer timeframes (greater than 10,000 years). The recommendations of the NRC's performance assessment working group, found in NUREG-1573, noted that there would be exceptions to the 10,000 year performance period recommendation. Disposal of large quantities of uranium or transuranics was one of the examples of an exception provided in NUREG-1573. The issue of the performance period was presented to the Commission in SECY-96-103. The Advisory Committee on Nuclear Waste (ACNW) expressed a similar concern as the performance assessment working group. The ACNW, in a February 11, 1997, letter to the Commission, stated:

> "The potential for significant quantities of certain long-lived radionuclides, such as uranium in near-surface LLW sites, is greater than was anticipated in the DEIS for 10 CFR Part 61. The result is that peak doses may not occur until a long period of time has passed, perhaps tens or hundreds of thousands of years. In addition, the risk from decay products may be higher than that of the parent. If the calculated doses at very long periods exceed the standard by significant factors, the LLW disposal system may require modification."

A required performance period for robust engineered barriers used in the disposal of Class C waste is specified in Part 61 as 500 years [10 CFR 61.52(a)(2)]. This performance period is necessary to ensure that the Class C waste can be protected from inadvertent intrusion until it decays to safe levels. Class C waste can be disposed of with a robust intruder barrier or be disposed of at depths below 5 m; either measure would be protective of public health and safety (see Part 61). The performance period for engineered barriers used to limit inadvertent intrusion and demonstrate compliance with 10 CFR 61.42 is not the same as the performance period for demonstration of compliance with 10 CFR 61.41, protection of the public. For example, demonstration of compliance with 10 CFR 61.41 typically involves assessment of radionuclide transport through groundwater pathways, and the associated travel time for some radionuclides is typically in excess of 500 years. The processes and pathways potentially leading to exposure to the public under 10 CFR 61.41 are typically indirect, whereas the processes and pathways leading to exposure to the public (inadvertent intruder) under 10 CFR 61.42 are direct. The peak doses for inadvertent intrusion usually occur in the year of intrusion, because commercial LLW contains a significant fraction of short-lived radionuclides, whereas the peak doses for demonstration of compliance with 10 CFR 61.41 are usually delayed as a result of transport through the environment. The performance period for engineered barriers, combined with the waste classification system, ensures that the public health and safety would be protected in the event of inadvertent intrusion into the waste.

Other waste management programs that use a period of performance include decommissioning, high-level waste (HLW) disposal, and management of mill tailings. Subpart E of 10 CFR Part 20 provides that the analysis for decommissioning of sites should estimate the peak annual dose within the first 1,000 years after decommissioning. However, at most, but not all, facilities undergoing decommissioning, the quantity of long-lived radionuclides of concern are generally limited. In addition, the contamination is generally distributed in the accessible environment and the analysis for unrestricted use assumes direct land use of the contaminated site. Because there is generally assumed to be direct (inadvertent) access to the contamination, the risk from long-lived radionuclides that may have long environmental transport times is captured with the 1,000 year period of performance.

The period of performance for geologic disposal of high-level nuclear waste is based on a number of considerations, including but not limited to: sufficient period of time to ensure safety of humans and the environment for the release of radiation following loss of integrity of engineered barriers; adequate time period to incorporate significant processes and events that impose greatest risk; restricted time period during which uncertainties can be prescribed with reasonable assurance; and sufficient time such that the source term is greatly reduced and roughly equivalent to the hazard from a natural ore body (NRC, 2001). The generic (i.e., for sites other than Yucca Mountain) standards and regulations for HLW disposal (40 CFR Part 191 and 10 CFR Part 60) specify a compliance period of 10,000 years. Site-specific standards and regulations have been developed for HLW waste disposal at Yucca Mountain, Nevada, as directed by statute. The compliance period for Yucca Mountain was specified in EPA's standard (40 CFR Part 197) at 10,000 years. However, the compliance period was remanded on a procedural basis because the findings and recommendations of the National Academy of Science (NAS) were not adequately considered as required by the Energy Policy Act of 1992. The NAS stated that compliance assessment is feasible for most physical and geologic aspects of repository performance on the time scale of 1 million years at Yucca Mountain. For HLW disposal, the NAS recommended that the compliance assessment be conducted for the time when the greatest risk occurs, within the limits imposed by the long-term stability of the geologic environment. As a result of the remand, EPA has proposed a revised standard (i.e., different dose limit, and further constraints for performance assessment for the period beyond 10,000 years) to address the difficulties and uncertainties in conducting analyses beyond 10,000 years.

The standards for the management of uranium mill tailings in 10 CFR Part 40, Appendix A, requires disposal in accordance with a design that provides reasonable assurance of control of radiological hazards for 1,000 years and, in any case, for at least 200 years. The standard also requires perpetual governmental ownership and long-term surveillance of the site (which may include monitoring as necessary). Therefore, no prolonged inadvertent access or use of the site is assumed during this period. Flux limits are applied for ^{222}Rn averaged over the cover system and standards for groundwater protection are specified. As discussed previously, two primary differences between the source terms for uranium mill tailings and DU are the concentrations of uranium and the initial and eventual concentration of daughter radionuclides. Depleted uranium has much higher initial concentrations of uranium and much lower initial concentrations of daughter radionuclides. However, the eventual concentrations of daughter radionuclides in DU will be much higher than mill tailings.

Internationally, there is no consensus on the approaches used for period of performance (NEA, 2002). Many countries consider a multi-step approach with early and longer assessment periods, although some countries do not specify a time of compliance. The NRC LLW regulations do not specify a period of performance. However, the documentation supporting the environmental impact statements for Part 61 and related guidance documents recognized the need to use a period of performance commensurate with the persistence of the hazard of the source (NRC, 1981; NRC, 1982; NRC, 2000). Selection of a period of performance generally considers the characteristics of the waste, the analysis framework (assumed scenarios, receptors, and pathways), societal uncertainties, and uncertainty in predicting the behavior of natural systems over time.

ANALYSIS FRAMEWORK

The primary objective of the analysis was to understand the impacts of key variables on the risks from disposing of DU as LLW such that staff could respond to Commission direction to consider whether the quantities of DU in the waste stream from uranium enrichment facilities warrant amending the waste classification tables in Part 61. Therefore, the current analysis used a framework similar to the analysis performed for the DEIS and FEIS supporting Part 61, as discussed below. Although computational tools and methods to incorporate and evaluate uncertainty have improved, and therefore, were used in the current analysis, staff believed the regulatory framework used in the development of Part 61 remains appropriate today.

Evaluation of protection of the general population from releases of radioactivity (10 CFR 61.41) was performed for leaching of contaminants to a water pathway and diffusion of radon to the atmosphere. The general population was assumed to reside offsite during the institutional control period, and then outside a buffer zone surrounding the disposal area boundary after the institutional control period. The model was structured such that the length of the institutional control period was evaluated in the analysis in order to assess the sensitivity of the results to the institutional control period. The protection of individuals from inadvertent intrusion was evaluated with acute and chronic exposure scenarios following either excavation into the waste, excavation above the waste but not into the waste, or drilling through the waste. The particular intruder scenario evaluated was based on the depth to waste. Below a disposal depth of 3 m, disruption of the waste via excavation was not believed to be credible for a resident-intruder scenario. Notable differences from the analysis performed to support Part 61 were (current analysis described): probabilistic assessment of uncertainty and variability, and use of updated dose conversion factors and the International Committee on Radiation Protection (ICRP) 26 and 30 dosimetry models. Also as previously noted, the purpose of the screening analysis was to evaluate key variables such as disposal configurations (disposal depth and barriers), performance periods, institutional control periods, waste forms, site conditions, pathways, and scenarios. Some of these variables were evaluated outside of ranges that may have been used in the LLW impacts analysis.

Key assumptions for the analysis included:

- Depleted uranium would be disposed of in an oxide form. The model included the capability to look at other forms, but those capabilities were not used in the analysis.
- Although smaller disposal quantities were evaluated, most analyses assumed approximately 300,000 m^3 of DU in the fluoride form would be converted to an oxide for disposal. The quantities assumed were 700,000 metric tons from DOE and 700,000 metric tons from operation of commercial uranium enrichment facilities (DOE, 2007; NRC, 2006; NRC, 2005).
- There was no co-disposal of other waste that would impact release or mobility of the DU.
- The basic disposal configuration was placement of 200 L carbon steel packages of DU in below ground disposal cells that were backfilled with native soil.
- The disposal system was assumed to have an engineered cover that would limit infiltration (performance set by the user in the analysis).
- The disposal system was assumed to have a clay layer as a radon barrier. The thickness of the clay was assumed to be 0.5 m for the results reported in this report.
- Additional performance credit of engineered features was not assumed, given the long-timeframes evaluated and the current types of technology used in near-surface disposal. Engineered features can have a large impact on performance, but justification of that credit beyond hundreds of years can be challenging.
- The liquid saturation of various materials in the analysis was temporally-invariant, but varied stochastically with each probabilistic realization.
- After the active institutional control period, the resident receptor would be located outside a buffer zone surrounding the disposal area.
- Site stability requirements would be achieved. There will not be significant releases of waste to the environment from fluvial or aeolian erosion.
- Extreme events, such as pyrophoricity, would be avoided through disposal conditions or other requirements.
- Soil-to-plant transfer factors are valid over the range of concentrations of radionuclides projected to be released to the soil from DU.
- Radon was included in the dose assessment. The concentration of radon that a member of the public is exposed to is equal to the atmospheric concentration over the site (e.g., the site is large enough such that additional dilution during transport to a receptor located at the disposal site boundary is limited).
- Radon gas was assumed to be transported through the system by diffusion. Barometric pumping was not included. The validity of this assumption is questionable for shallow disposal depths in arid environments in particular. However, under those conditions, the doses were sufficiently large that the primary output metric of whether the system could meet the performance objectives would not be impacted (i.e., the results already exceeded the performance objectives).
- The quantity of material being disposed is sufficiently large such that lateral dispersion during transport through groundwater can be neglected.
- Colloidal transport was neglected.

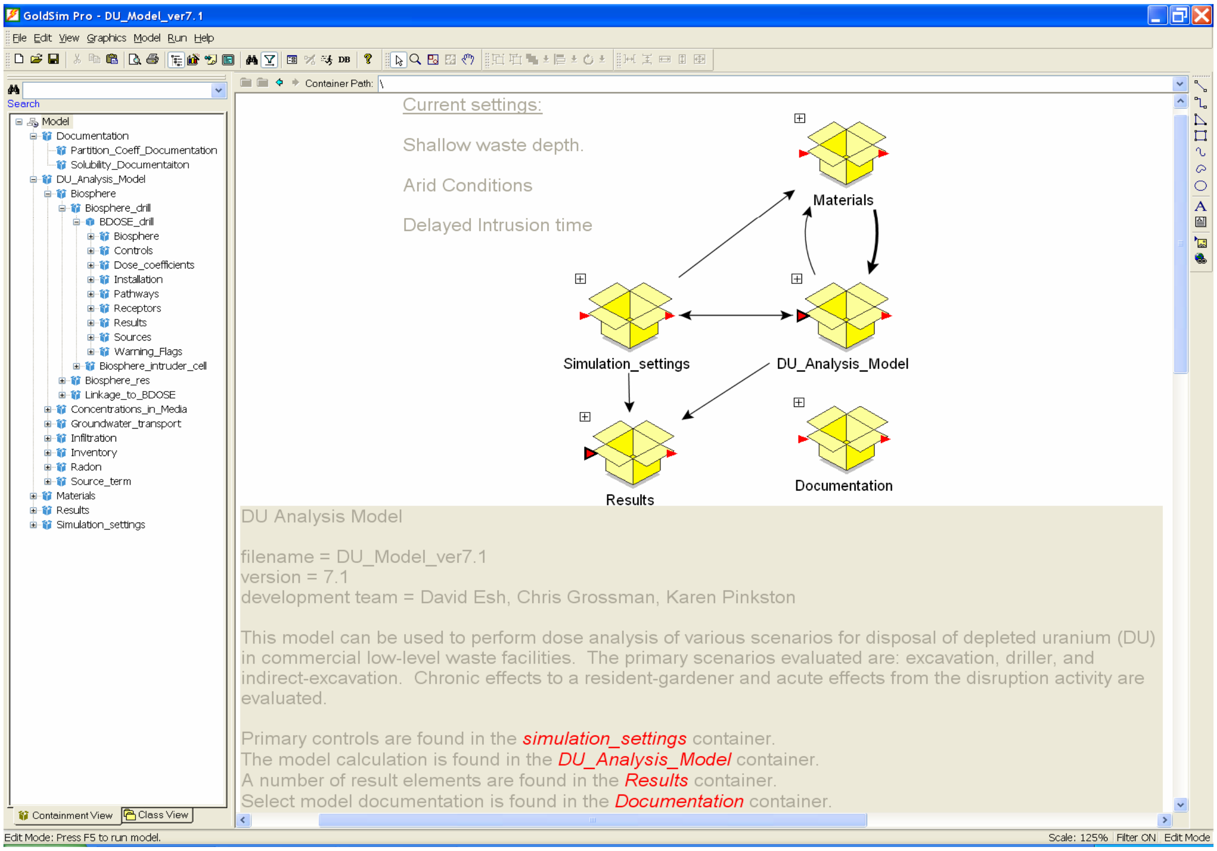
MODEL DESCRIPTION

A screening model was developed as a first-order assessment tool to evaluate the radiological risk to future residents and intruders (acute or chronic exposures) near or on the land overlying a hypothetical disposal facility for DU. The model was designed to provide the user with flexibility to evaluate different waste types and forms (e.g., fluoride types, oxides types, powdered forms, and solid forms), disposal configurations, performance periods, institutional control periods, pathways, and scenarios. Refinement of the model would be necessary if it was to be used for licensing decisions, and rigorous validation would be needed. Because site-specific waste management decisions or other variables can strongly influence whether performance objectives can be met, the results should not be taken out of the analysis context.

The model was constructed with the dynamic simulation software package GoldSim®. A hierarchical design to the modeling was used with containers to organize information. At the top level, containers are provided for *Simulation_Settings*, *Materials*, *DU_Analysis_Model*, *Results*, and *Documentation*. Figure 3 provides a screen snapshot of the top level of containment for the model. For version 7.1, the model contains 3,252 GoldSim elements of 19 different types with 10 levels of containment. Stochastic inputs are specified for over 400 variables. Figure 4 provides a screen snapshot of the model structure within the *DU_Analysis_Model* container. The hierarchical design and use of submodels facilitated different team members working on different portions of the model concurrently. The arrows in Figure 4 show the flow of information between containers in the model. The time to execute 100 realizations (repetitions of a probabilistic simulation) is approximately 7 minutes on a quad core 2.66 gigahertz (GHz) personal computer with 3 gigabytes (GB) of random access memory (RAM).

Most controlling parameters for a simulation were organized in the *Simulation_settings* container. This container provides various controls such as parameters for specifying the intrusion time, waste depth, pathway settings (e.g., turn radon or groundwater on/off), and residential properties (presence or absence of a basement, location of the resident with respect to the buried source). Within the *Simulation_settings* container are containers for intruder settings, such as well properties and excavation properties, and source input settings. Source input settings are clones of other elements within the model to allow the user ease of access to change the waste form type, site environment (i.e., humid or arid), and presence of grout. Clones are duplicates of model elements that, when edited, propagate the changes to all of the associated clones.

The *Materials* container provides the species element, solubilities, solids, partition coefficients, and tortuosity calculations. The species element for this model is a vector of the radioisotopes provided in the model including their half-lives and decay chains. The current model explicitly considers 11 radionuclides, although one of the radionuclides is a dummy of ^{222}Rn used to incorporate the effect of variation in emanation, such as if the DU was grouted. The model contains seven different types of solid phases, each which can have different physical properties such as density, porosity, tortuosity, and partition coefficients. Tortuosity of the partially saturated porous media in the engineered cap is specified with one of five different methods. Particular approaches for modeling some of the technical aspects are discussed in further detail in the following paragraphs. The *Results* container provides selected outputs, such as plots of dose histories by scenario, pathway, or radionuclide.



Current settings:

Shallow waste depth.

Arid Conditions

Delayed Intrusion time

DU Analysis Model

filename = DU_Model_ver7.1
version = 7.1
development team = David Esh, Chris Grossman, Karen Pinkston

This model can be used to perform dose analysis of various scenarios for disposal of depleted uranium (DU) in commercial low-level waste facilities. The primary scenarios evaluated are: excavation, driller, and indirect-excavation. Chronic effects to a resident-gardener and acute effects from the disruption activity are evaluated.

Primary controls are found in the *simulation_settings* container.
The model calculation is found in the *DU_Analysis_Model* container.
A number of result elements are found in the *Results* container.
Select model documentation is found in the *Documentation* container.

Figure 3 Top-level Containment of the DU Analysis Model

Main submodels include inventory, source term, infiltration, radon, groundwater transport, and biosphere. Submodels use both deterministic and probabilistic input values or distributions. Submodels can be summarized as:

- The inventory model allows the user to specify the quantity and radiologic distribution of the source. The model includes ^{238}U, ^{235}U, ^{234}U and their associated decay chains. Decay chains have been simplified by including the dose contribution of short-lived daughters with the parent radionuclide using a half-life cut off of 30 days. The ^{234}U decay chain explicitly included: ^{230}Th, ^{226}Ra, ^{222}Rn, ^{210}Pb, and ^{210}Po. The ^{238}U decay chain included ^{234}U and its daughter radionuclides previously listed. The ^{235}U decay chain included: ^{231}Pa and ^{227}Ac. The decay of ^{226}Ra is fractioned to ^{222}Rn and a dummy radionuclide, ^{222}Du, to account for emanation loss of ^{222}Rn. This approach results in a decrease in the source concentration of radon, and therefore, decreases the diffusion rate of radon from the source. The fraction of ^{226}Ra that decays to the ^{222}Du is immobile as ^{222}Du. The ^{222}Du decays in place to the next member of the decay chain, thereby not impacting the groundwater pathway calculation.

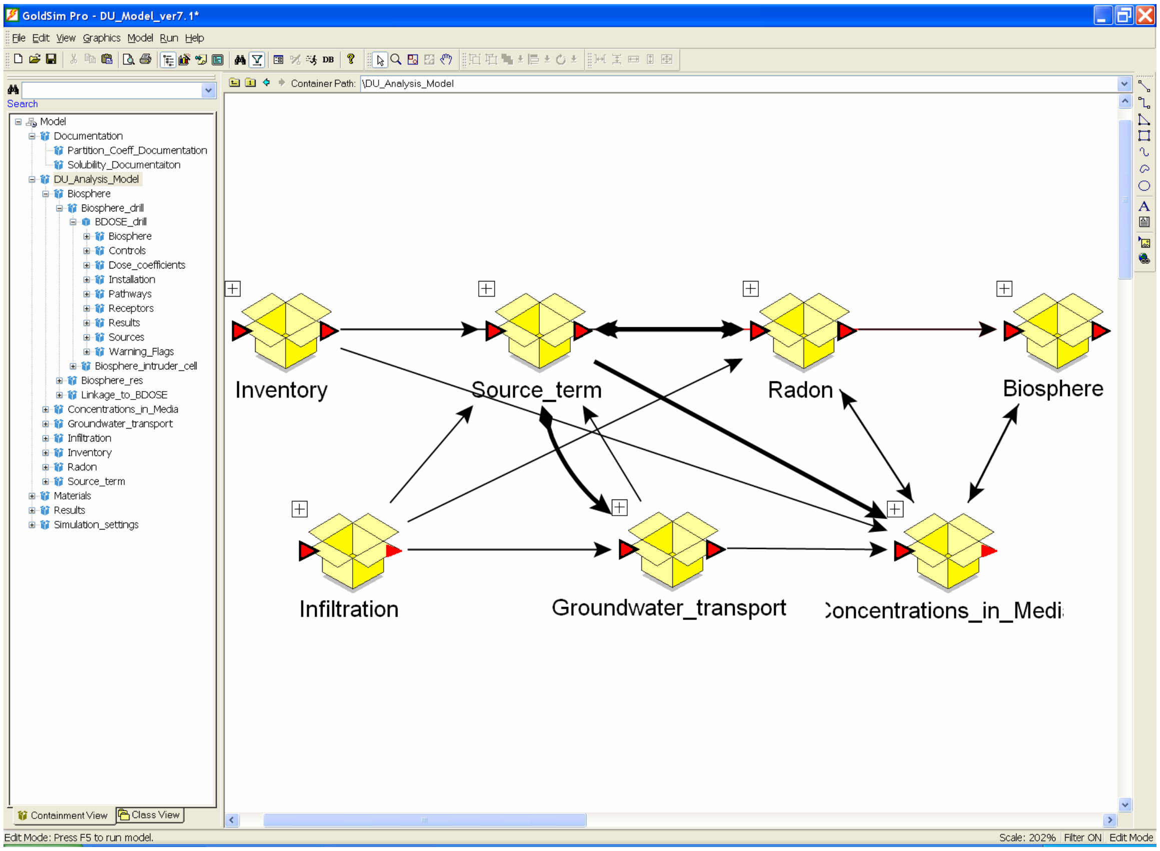


Figure 4 Model Structure within the Main Model Container

- The source term submodel is used to define the quantity, type, and form of the material being disposed; its associated physical and chemical properties; and the geometry of disposal (waste thickness, depth, etc.). The source term submodel can represent the failure of waste containers over time as well as the gradual degradation of the waste form. Waste released from the waste form is available for partitioning between media and release from transport processes. The source term model applies distribution coefficients, based on material type, to partition radionuclides between solid and liquid phases. Solubility limits are also applied, in addition to partitioning, to estimate liquid phase concentrations of radionuclides. The model makes use of cloning of elements with localized containers to apply different solubility limits in different portions of the model. Localization of a container prevents the model portions outside of the container from seeing or manipulating the contents inside the container unless the user specifies otherwise. Partition coefficients are selected with multi-dimensional lookup tables based on sampled values for liquid saturation, pH, and carbonate concentration. An environmental condition switch is used to represent different site types (e.g., humid or arid) by selecting different liquid saturation, pH, and carbonate concentrations. The calculated partition coefficients from this approach were compared to literature values. Numerous references were used to develop the lookup tables and are found in the reference section of this report.

- The infiltration submodel is an abstracted representation of what are complex and dynamic physical processes; the infiltration rate is not calculated in the model but is specified by the user of the model. The user specifies the effectiveness of an engineered cap to reduce infiltration, and how the performance of the cap decreases over time. This approach allows ease of use to evaluate a full range of infiltration scenarios. Complex infiltration rate profiles could be provided; however, the current analysis was for hypothetical sites without specific infiltration rate data or engineered cover designs. In most analyses, the infiltration cover was assumed to lose its effectiveness a few hundred years after site closure. For arid sites, the long-term infiltration rate was assumed to be on the order of a few millimeters per year. For humid sites the long-term infiltration rate was assumed to be on the order of tens of centimeters per year.

- The radon submodel is used to estimate the flux of radon into the interior of a residence placed over the disposal area or to the external environment. Radon that emanates from radium present in the DU is modeled as diffusing to the surface through an engineered cap. The engineered cap contains a clay layer as well as a soil layer. The thicknesses of the layers are specified by the user. Modeling of radon transport in partially saturated media is subject to a high degree of uncertainty. The gas phase diffusion of radon in partially saturated porous media is highly dependent on the saturation of the media. To take this into account, the tortuosity used in the diffusion calculations is corrected for the saturation of the pore space in the soil and the clay. The model allows the use of one of five different relationships between tortuosity and saturation. The outdoor concentration of radon is calculated by modeling the air above the site as a mixing cell in which the radon is diluted and removed by wind. If a residence is located over the DU disposal area, the radon is also modeled as diffusing through the foundation of the house and into the house. The indoor concentration of radon is calculated by modeling the interior of the house as a mixing cell that has inputs from the diffusive flux of radon from the subsurface and from radon that is brought in from the outdoor air through the ventilation system. Staff compared the estimated radon fluxes with values calculated using Regulatory Guide 3.64 (NRC, 1989).

- Because the assessment was designed to evaluate a range of sites, the groundwater transport modeling was relatively simple from the perspective of temporal and spatial variability. Transport through the unsaturated zone was assumed to be vertical to the saturated zone; transport through the saturated zone was assumed to be horizontal or lateral to a receptors well. Groundwater transport through the unsaturated zone is represented with a series of mixing cells. Advection, partitioning between liquid and solid phases, solubility limits, and decay and in-growth are included in the mathematical representation of a cell. Diffusion can be included in cell elements but has not been included in the current representation because advective transport of radionuclides dominates diffusive transport except under very low flow conditions. Cell elements implicitly include dispersion. Groundwater transport through the saturated zone is represented with GoldSim pipe elements. Pipes are modeled as reactive columns and include advection, partitioning between liquid and solid phases, decay and in-growth, and dispersion. Additional features are available with pipe elements, such as exchanges between immobile storage zones (e.g., matrix diffusion), that are not used in the current analysis. The flux of radionuclides from the unsaturated zone is mixed in the saturated zone based on the characteristic length of the source (the square root of the source area) and a user-defined well screen depth typically set at approximately 5 m. The flow of water entering the saturated zone pipe is based on the hydraulic gradient and hydraulic conductivity of the saturated zone. Because the analysis was generic and hydrologic systems can have widely variable properties, the input distributions were fairly wide, resulting in hydraulic residence times in the pipe from less than ten to greater than 1,000 years.

- The concentration in media model component is used to provide the outputs of radionuclide concentrations from the source, radon, and groundwater submodels for use in the biosphere submodel to estimate radiological risk.

- The biosphere submodel utilizes the probabilistic dose model BDOSE developed for the NRC by the Center for Nuclear Waste Regulatory Analyses (Simpkins, et al. 2007). BDOSE was verified by hand calculation and comparison to RESRAD. The submodel considers unit inputs of groundwater concentrations and estimates dose for a resident farmer or a resident gardener. Acute and chronic intruder scenarios are also considered, using inputs of actual waste concentrations with units of activity per unit volume. Exposure pathways include external exposure from surface, air, and water; internal exposure from inhalation of air; and internal exposure from ingestion of drinking water, vegetables/fruits, milk, beef, game, fish, and soil. The submodel provides flexibility in defining specific exposure pathways for each receptor type. Within BDOSE, individual receptor pathways are established by selecting to include or exclude possible pathways in a defined *Pathway vector* that defines a receptor. Potential pathway doses are stochastically evaluated for each receptor type and pathway, based on user defined ingestion, inhalation rates, and exposure time distributions. Key biosphere model settings within BDOSE are controlled by switch elements that are centrally located in a single *Controls* module. Switches and data elements were included to allow the user to control aspects of the analysis such as: the use of alternative dose coefficients (ICRP 72 or Federal Guidance Report No. 11 (EPA, 1988)) for internal radionuclide dose calculations, the time for loss of institutional controls, the model used to evaluate soil concentrations, the exposure to different types of contaminated water sources, and receptor pathway definitions. BDOSE is supplied with seven soil models that can be used to evaluate radionuclide buildup in the soil from irrigation with contaminated groundwater. These multiple models provide various considerations for deposition processes (irrigation and in-growth) and removal processes (decay, soil erosion, and leaching into deep soil). BDOSE evaluates radionuclide concentrations for several animal products including: beef, milk, poultry, eggs, fish, and game. BDOSE evaluates radionuclide concentrations for multiple vegetation types, including those used for human consumption (vegetables, leafy green vegetables, fruits, and grains), and those used for animal feed (animal specific grains and fodders). For a full description of BDOSE see Simpkins et al. (2007).

Figure 5 is a diagram of the conceptual model evaluated in the analysis, with the main elements of the problem. Figure 5 does not reflect every scenario or configuration evaluated in the analyses, but is intended to give an overview of the basic conceptual model. The dashed line on Figure 5 delineates the two primary types of receptors: resident or intruder. The DU source releases to a backfill assumed to surround the DU in the disposal cells. Radon can partition between the gas and liquid phases, and diffuse in the gas phase through clay, soil, and basement foundation layers, as applicable. Radionuclides released to the backfill are vertically transported via advection through unsaturated zone cells to an underlying aquifer, where they are transported to a receptor well. Contaminated water is then extracted and used for farming or domestic purposes. Figure 6 shows the primary transport pathways implemented in the GoldSim model. The clay, soil, and foundation elements are comprised of many GoldSim cells in order to limit numerical dispersion (not shown on the figure).

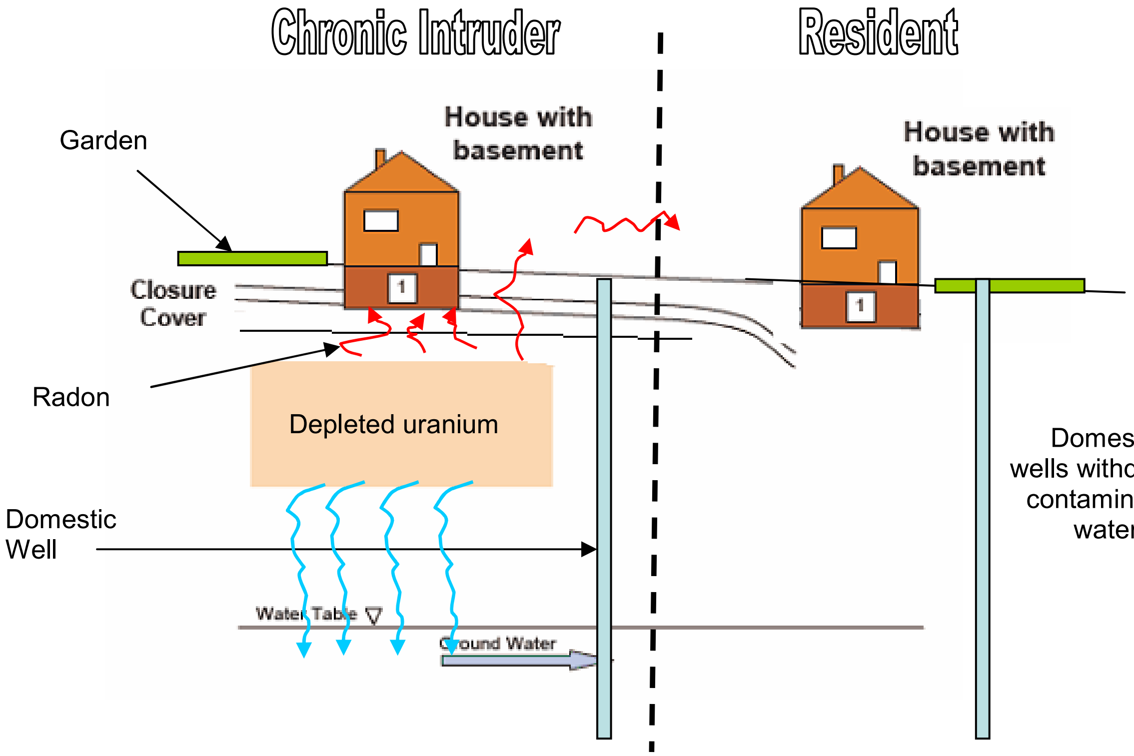


Figure 5 Conceptual Model Showing the Primary Scenarios.

KEY RESULTS AND UNCERTAINTIES

The model was used to evaluate whether large quantities of DU can be disposed of in the near-surface as commercial LLW. Key variables evaluated included: disposal configurations, performance periods, institutional control periods, waste forms, site conditions, pathways, and scenarios.

Summary Results

- Depleted uranium has characteristics that are dissimilar from commercial LLW:
  - Large percentage of the activity is associated with very long-lived radionuclides
  - Decay results in increasing hazard with time until after 1 million years, as a result of increasing concentrations (and higher mobility) of decay products
  - In-growth of significant quantities of a daughter in gaseous form (^{222}Rn)
- Estimated risks are sensitive to the performance period.
- Estimated risk from radon is sensitive to the disposal depth.
- Radon fluxes to the environment are very sensitive to the long-term moisture state of the system.
- Large uncertainties (and little available data) associated with some transfer factors for uranium daughter products.
- Estimated disposal facility performance is strongly dependent on site-specific hydrologic and geochemical conditions.
- Radon is major contributor at arid sites with shallow disposal.
- The groundwater pathway is limiting at humid sites.

- Grouting of the waste may improve the likelihood of an arid site meeting the performance objectives; however, grout may enhance the mobility of uranium in the groundwater pathway after the grout degrades.

The summary conclusions from the technical analysis are:

- Near-surface disposal (i.e., less than 30 m, as defined in Part 61) may be appropriate for large quantities of DU under certain conditions. However, unfavorable site conditions can result in the performance objectives not being met. Examples of unfavorable conditions include shallow disposal (< 3 m depth) and humid sites with a potable groundwater pathway.
- Because of the in-growth of radon and other daughter products, periods of performance of 1,000 years or less result in a significant truncation of estimated risk.
- Shallow disposal (< 3m deep) is likely to not be appropriate for large quantities of DU, regardless of site conditions. Shallow disposal may be possible if robust intruder barriers, excluding the possible excavation of DU, and a robust radon barrier that can effectively limit radon fluxes over the period of performance are installed, and their performance is justified. Small quantities (1 – 10 metric tons) could be disposed of at shallow depths.
- Depleted uranium can be disposed of under arid conditions and meet the Part 61 performance objectives for 1,000 to 1 million years performance periods, if the waste disposal depth is large, or robust barriers are in place to mitigate radon.
- Disposal under humid conditions with viable water pathways is probably not appropriate for large quantities of DU.

Detailed Results

As noted above, disposal facility performance is strongly dependent on site-specific hydrologic and geochemical conditions. There is a large amount of uncertainty in a generic assessment, such as this one, and the associated risk insights should not be interpreted as anything more than providing understanding for decision making. The assessment was designed to be a first-order evaluation of key variables, and should not be misinterpreted as providing more information than a first-order assessment. The additional challenge, from a technical perspective, is presenting the results. Site-specific hydrologic conditions such as infiltration rates, liquid saturation, hydraulic gradient, unsaturated zone thickness, hydraulic conductivities, and geochemical conditions, such as pH and carbonate, and the resultant partition coefficients and solubilities were represented in the analysis as epistemic uncertainty over a broad range of sites. In reality, many of these parameters can be constrained for a particular site and disposal system. For example, uranium solubility limits applied in this model represent dissolved concentrations for a range of environmental conditions. Primary environmental factors for uranium solubility include the reduction-oxidation potential, pH, and dissolved carbonate concentration. Reducing conditions, such as those that may be present due to cementitious phases, as in reducing grout, typically result in sparingly soluble uranium species. Solubility limits for uranium, as applied in this model, can be as low as 10^{-8} moles per liter such as may

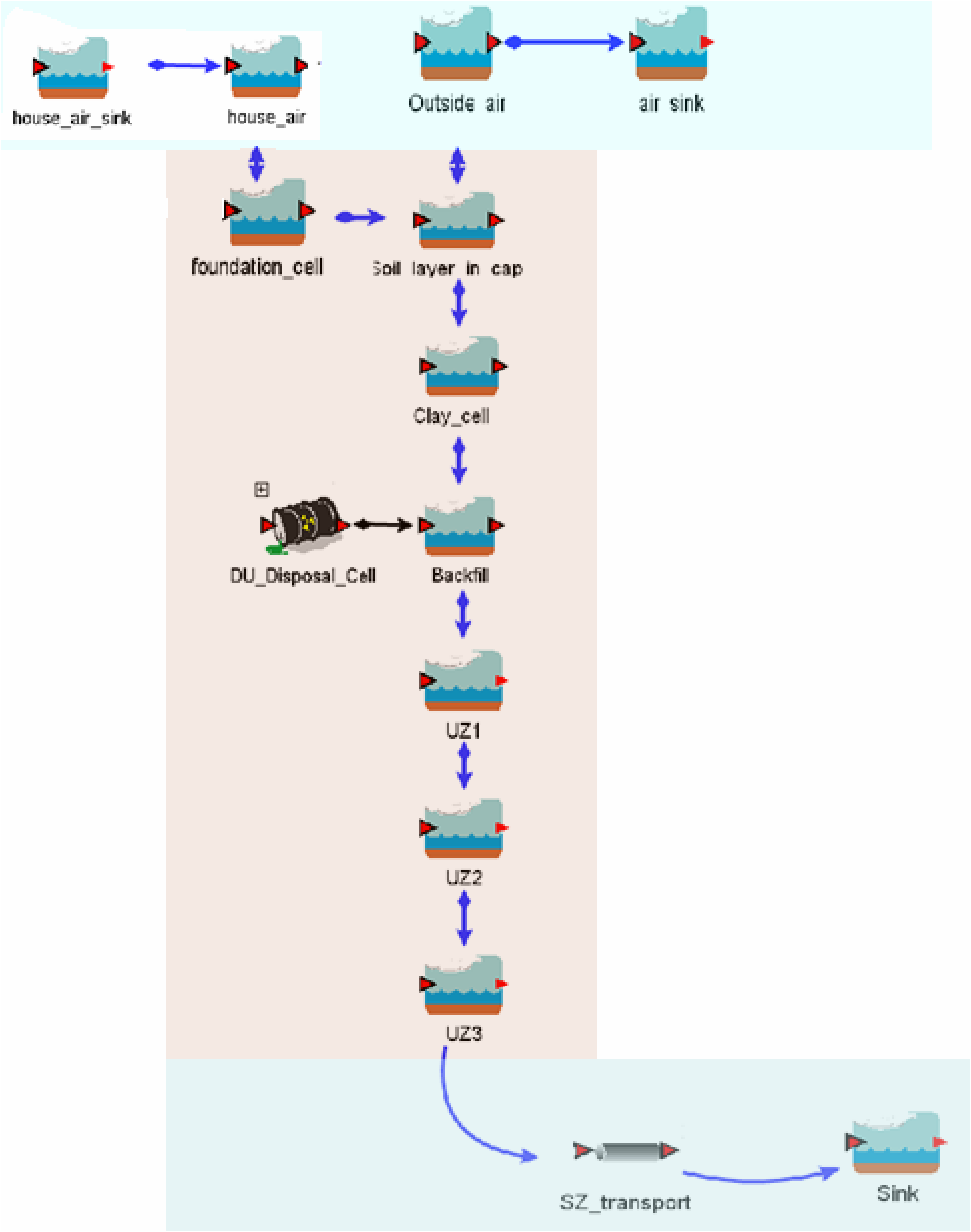


Figure 6 Main Transport Pathways Implemented in the GoldSim Model

occur under strongly reducing conditions. In contrast, under increasingly oxidizing conditions, uranium tends to exhibit more soluble species. The solubility of uranium under oxidizing conditions can vary over a wide range of concentrations and may include unlimited solubility. In addition, the presence of complexing ligands, principally carbonates at pH ranges typical of oxidized natural waters, can influence the solubility of uranium. The model represents this uncertainty for oxidizing conditions by varying solubility limits over many orders of magnitude as a function of pH and carbonate concentration. For an arid site with oxidizing conditions, the solubility of uranium generally varied from 10^{-6} to 10^{-4} moles per liter.

A typical output that NRC staff evaluates for a probabilistic analysis is the peak of the mean dose curve. The peak of the mean dose curve is compared to the performance objective (e.g., 25 mrem/yr). In this type of analysis, the peak of the mean is not the appropriate output

Table I Percent of Probabilistic Realizations that Meet the Performance Objectives

Scenario	**Performance Period (yr)**	**Resident[1]**			**Chronic Intruder[2]**
		Total dose	**Drinking water**	**Inhalation**	**Total dose**
Arid, 1 m disposal depth	1,000	**100**	**100**	**100**	<2
	10,000	40	**90**	**50**	0
	100,000	10	**60**	20	0
	1,000,000	<1	40	8	0
Arid, 3 m disposal depth	1,000	**100**	**100**	**100**	2
	10,000	**80**	**90**	**100**	0
	100,000	**50**	**60**	**80**	0
	1,000,000	20	40	**70**	0
Arid, 5 m disposal depth	1,000	**100**	**100**	**100**	**100**
	10,000	**80**	**90**	**100**	**100**
	100,000	**50**	**60**	**90**	**90**
	1,000,000	30	40	**90**	**70**
Humid, 5 m disposal depth	1,000	**70**	**70**	**100**	**100**
	10,000	0	0	**100**	20
	100,000	0	0	**100**	0
	1,000,000	0	0	**97**	0
Arid,[3] 5 m disposal depth, Grout	1,000	**100**	**100**	**100**	**100**
	10,000	**90**	**90**	**100**	**100**
	100,000	**70**	**70**	**100**	**90**
	1,000,000	**60**	**60**	**90**	**80**

[1] Percent of realizations that are below 25 mrem/yr total effective dose equivalent (TEDE). The resident consumes contaminated plants raised at the site, but does not consume contaminated animals. The results for the resident do not have radon diffusing into the basement, but the resident does get exposure to radon in the ambient environment while outdoors and indoors. Results are rounded to one significant figure.

[2] Percent of realizations that are below 500 mrem/yr TEDE. When the waste depth is greater than 3 m, the waste disruption process is through well drilling, not home excavation.

[3] The performance of grout over long periods of time is very uncertain. If the initial low leachability of grouted waste can be maintained, a performance benefit can be realized.

statistic, because the mean is strongly affected by a few extreme results which would represent an unfavorable site or disposal system. It is more informative to look at the median result or the fraction of probabilistic realizations that may be above or below certain values. This information could be interpreted as reflecting the likelihood that a specific scenario or configuration could achieve a particular outcome.

Table I provides the percent of realizations that meet the applicable dose limits of 25 mrem/yr to the public and 500 mrem/yr to the intruder for a variety of scenarios and configurations. Figure 7a provides example dose plots for the resident receptor and Figure 7b provides the results for the same calculation by exposure pathway. The results shown on Figure 7b are the mean dose for each pathway. The results in Table I demonstrate that performance period, disposal depth at arid sites, and site conditions are important variables to consider for the disposal of DU. With a short performance period, many sites and disposal configurations would be able to meet the performance objectives. For an arid site, radon has not ingrown sufficiently when the performance period is short (1,000 years). For both arid and humid sites, the delay in transport is sufficient to achieve the performance objectives, except for shallow disposal. Disposal of large quantities of DU at depths less than 3 m results in projected chronic intruder doses much in excess of 500 mrem/yr. At longer performance periods and if water from the aquifer is used for consumption or for other domestic practices, such as irrigation, disposal under humid conditions would likely not meet the performance objectives. Disposal under arid conditions can achieve the performance objectives and the likelihood of compliance is significantly improved if the disposal depth is larger.

An uncertainty analysis was performed using genetic variable select algorithms using a neural network software product, Neuralware NeuralWorks Predict® (Neuralware, 2001). For the water dependent pathways at an arid site, important parameters were the hydraulic conductivity and gradient of the aquifer, the infiltration rate, and geochemical conditions that determine sorption and solubilities. For radon at an arid site, the liquid saturation of the materials and properties of the residence and scenario, such as house height, foundation porosity, air exchange rate in the house, and fraction of time spent indoors, were most significant. For animal pathways, there is very limited data on transfer factors for some of the daughter radionuclides. Additional research may be needed to develop more robust estimates of transfer factors.

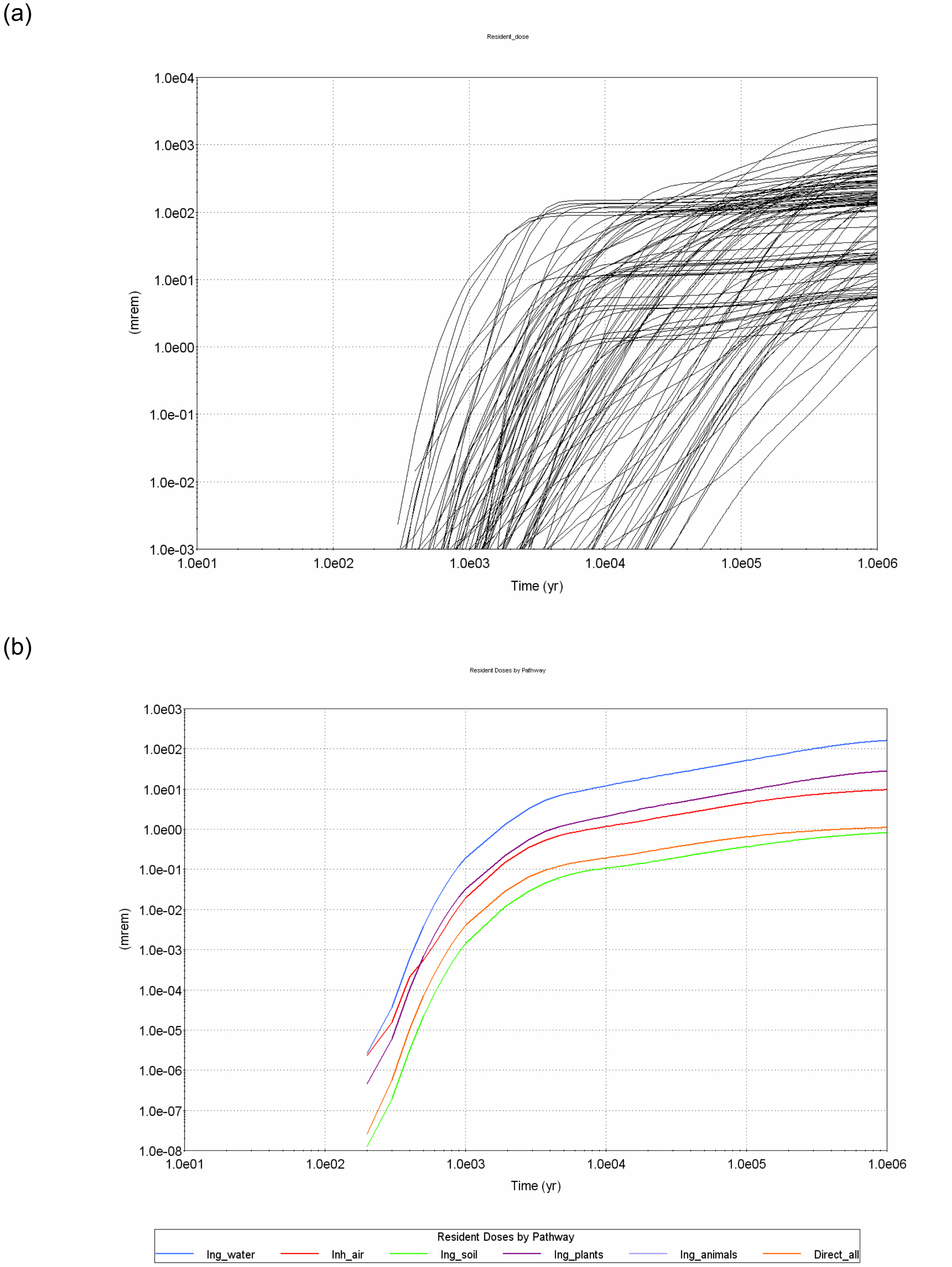


Figure 7 (a) Example of Dose Histories Generated for a Probabilistic Simulation. (b) Dose Histories for a Resident Calculation by Exposure Pathway. The lines from top (highest) to bottom are: ingestion of water, ingestion of plants, inhalation (primarily radon), direct radiation, and ingestion of soil. Shown is the mean result by pathway for 100 realizations.

CONCLUSIONS AND RECOMMENDATIONS

Near-surface disposal of large quantities of DU may be appropriate, but not under all site conditions. It is important to note that this same conclusion would likely be reached for the disposal of commercial LLW, if it was evaluated in this analysis. However, the types and degree of constraints would be different for disposal of large quantities of DU in the near-surface compared to typical LLW. The requirements provided in Part 61 are intended to ensure that unfavorable conditions for commercial LLW disposal will be avoided. The characteristics of DU differ from commercial LLW. As shown in Figure 1, the radiologic hazard of DU is more persistent than typical commercial LLW. It also has a much lower initial specific activity compared to its eventual specific activity, which is a problem because confidence is higher shortly after disposal that institutional controls will be maintained, engineered barriers will perform their function, and stability of the disposal site can be ensured. Therefore, whereas commercial LLW requires a greater level of protection with respect to direct radiation and impacts to workers, DU requires a greater consideration of long-term stability and isolation from the accessible environment over longer timeframes. It is recommended that large quantities of DU be disposed of at a minimum of 3 m from the current land surface, if the land surface is stable, or the future land surface as estimated by geomorphologic projections over the compliance period. Ideally, even deeper disposal depths would be favorable for mitigating long-term radon hazards associated with the disposal of DU. Site-specific hydrologic and geochemical conditions should be carefully considered in assessment of the risk impacts from the disposal of large quantities of DU in the near-surface. The uranium parents and some of the daughter products can be moderately mobile in the environment. The quantity and concentration of the source, combined with the moderate mobility, can result in it being very difficult to achieve the 10 CFR 61.41 performance objective under humid conditions, if potable aquifers or aquifers that are used for irrigation of plants for human or animal consumption are impacted. Therefore, disposal of large quantities of DU under humid conditions is not recommended.

Considering the technical aspects of the problem, the performance assessment staff recommends a performance period of *10,000 years* for the analysis of *DU* disposal. However, analyses should be performed to peak impact, and if those impacts are significantly larger than the impacts realized within 10,000 years, then the longer term impacts should be included in the site environmental evaluation. This recommendation is consistent with previous NRC guidance found in NUREG-1573 and considers the characteristics of the DU and uncertainty in estimating societal behavior and engineered and natural system performance over very long periods of time. Uncertainty in the projected doses from factors other than the physical characteristics and transport parameters of the system likely dominate at times larger than 10,000 years. Potentially high doses relative to the performance objectives could occur within a timeframe longer than 10,000 years from the disposal of large quantities of DU. However, the majority of sites, waste forms, and disposal configurations that can meet the performance objectives at 10,000 years will continue to meet the performance objectives at longer time periods. A simple approach that should be considered to ensure the eventual risk of radon is managed is to select a waste disposal depth and cover thickness based on the projected peak in-growth of the daughter species, rather than the in-growth over the performance period.

It is essential that the site hydrology and geochemistry be well-understood, because site-specific conditions are the primary determinant of the safety of the near-surface disposal of large quantities of DU. Uranium and daughter radionuclide speciation and partitioning, as well as, radon transport in natural systems are complex processes; the analysis of the near-surface disposal of DU must adequately evaluate and manage this uncertainty. Under improper disposal systems, configurations, or unfavorable site conditions, disposal of significant quantities of DU can exceed the 10 CFR 61.41 and 10 CFR 61.42 performance objectives by a significant margin. The analysis to assess performance of DU disposal at a particular site should be supported by as much site-specific data as practical. In particular, measurements of infiltration rates, radionuclide sorption and solubilities, radon diffusion and emanation rates, waste release rates, and soil-to-plant transfer factors can greatly reduce the uncertainty in the estimated future performance of a disposal site.

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