Technical Analysis Supporting Definition of Period of Performance for Low-Level Waste Disposal

Introduction

A value for the performance period[1] 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 Low-Level Waste (LLW) facility. But a performance period of 10,000 years was evaluated as part of the NEPA analysis in the Draft Environmental Impact Statement (DEIS) for Part 61 (NUREG-0782).

Part 61 requires the use of a 500-year performance period for robust engineered barriers used in the disposal of Class C waste [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. The performance period for engineered barriers used to limit inadvertent intrusion and demonstrate compliance with 10 CFR 61.42—*Protection of individuals from inadvertent intrusion* is not the same as the performance period for demonstration of compliance with 10 CFR 61.41—*Protection of the general population from releases of radioactivity*. For example, demonstration of compliance with 10 CFR 61.41 typically involves assessing the radionuclide transport through groundwater pathways, and the associated travel time for some radionuclides is typically in excess of 500 years. Section 61.41 assesses the indirect processes and pathways potentially leading to exposure to the public, whereas section 61.42 assesses the direct processes and pathways. The peak doses for inadvertent intrusion usually occur in the year of intrusion because commercial low-level waste contains a significant fraction of short-lived radionuclides. Whereas the peak doses associated 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 is protected in the event of inadvertent intrusion into the waste.

The period of performance is one of many important elements in the evaluation of the safety of radioactive waste disposal. The purpose of this paper is to provide the background, important considerations, options, and a recommendation for selection of a period of performance for low-level waste disposal.

Background

Within the NRC, the debate concerning the specification of an appropriate period of performance for waste disposal extends back as far as 1994. A variety of groups internal and external to the NRC discussed the merits of various approaches to defining a period of performance for waste disposal.

The Advisory Committee on Nuclear Waste (ACNW) noted that the numerical value for the period of performance for low-level radioactive waste, 10,000 years, was arbitrary and lacked bases in either standards or regulations (Steindler, 1994). The ACNW recommended the time

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[1] Different terminology has historically been used to refer to the timeframe assessed for regulatory compliance or other analyses including performance period, time of compliance, compliance period, and other variants. The terms performance period and period of performance are used throughout this document.

frame for site-specific performance assessments be guided by dose and time considerations, and that the timeframe should be tailored to the hazard of the low-level waste form being evaluated for disposal. In 1995, the National Academy of Sciences (NAS) concluded that there was no scientific justification or basis for specifying a truncation of the analyses at 10,000 years or at any other period of time for geologic disposal of high-level waste at Yucca Mountain, NV (NAS, 1995).

In the context of developing low-level waste performance assessment capability, the NRC formed the performance assessment working group[2] (PAWG) to engage both the public and stakeholders on this and other performance assessment-related topics. The staff presented the issue of the performance period to the Commission in SECY-96-103 (NRC 1996a) and recommended a 10,000 year compliance period; the Commission directed the staff to provide the technical basis used to support truncation of the performance assessment at 10,000 years (NRC 1996b). Around this time, the ACNW suggested regulatory principles that could be used to establish the time span for compliance (Pomeroy, 1996). The ACNW recommended a two-tiered approach: The first tier would be established by consideration of (1) The estimated time for release and transport of the radionuclide contaminants to reach the critical group, (2) The definition of a reference biosphere and lifestyle of the critical group, and (3) Uncertainty, which should be reasonably modest so as to allow extrapolation of significant processes. The second tier would be used to evaluate the robustness of the facility over long periods of time and should not become *de facto* regulation; the performance objectives for the first tier were not to be applied for the second tier. With respect to a compliance period for the Yucca Mountain repository, the ACNW believed that the first tier should be defined using existing knowledge of the engineering and scientific aspects of the facility and the environment. They noted that the time span for the compliance period should be no shorter than an estimate of the anticipated time it takes for potential radionuclide contaminants to reach the nearest critical group and no longer than a time period over which scientific extrapolations can be convincingly made.

In a further expansion of that position, the ACNW advocated a two-tiered approach for the period-of-performance analysis for low-level waste: The first tier would have focused on the evaluation of the behavior of the more mobile radionuclides for some specified period of performance. The duration of the period of performance would have been selected: (1) consistent with the radiological hazard; and (2) to reasonably account for the uncertainties associated with the calculation (Pomeroy 1997). The second tier would have evaluated the robustness of the disposal facility (and site) in light of the presence of any less mobile radionuclides. This calculation would have been used qualitatively to better understand when the peak dose might occur as well as its timing in relation to the period of performance defined by the first tier. The analysis would have emphasized the identification of risk factors contributing to peak dose and potential management strategies to address those risks. The ACNW highlighted the difficulty in selecting a single period of performance for all low-level wastes, which can have different waste characteristics. The ACNW, in a February 11, 1997 letter to the Commission, stated (Pomeroy 1997):

> "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

[2] The performance assessment working group (PAWG) was comprised of past and (then) present staff of the NRC to provide information and recommendations on performance assessment methodology as it relates to 10 CFR 61.41.

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."

The ACNW recognized the importance of considering deleterious surface processes such as erosion. They noted that engineered and natural barriers may delay releases for long periods of time. The ACNW continued to advocate this binary approach to period of performance in later correspondence (Garrick 2000).

In 2000 the PAWG published NUREG-1573, *A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities* (NRC, 2000). The staff proposed a 10,000-year period of performance to demonstrate compliance with 10 CFR 61.41, citing its consistency with other allied standards and authoritative technical recommendations. Supporting the recommendation were calculations the staff had performed for a hypothetical low-level waste disposal facility (Cady and Thaggard 1994). The staff's low-level waste test-case calculations, which had been conducted for as long as 100,000 years, were part of the basis for the recommendation of a 10,000 year period of performance. The performance assessment working group believed that a typical commercial low-level waste facility (one that was considered in the development of Part 61) would receive large amounts of short-lived waste that would decay to relatively innocuous levels within hundreds of years and contained limited amounts of long-lived waste. The PAWG considered a 10,000-year performance period sufficient to capture the risk from the short-lived radionuclides (the bulk of the activity disposed) and 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 PAWG, 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 provided in NUREG-1573 (NRC 2000). In NUREG-1573, the staff advocated the use of a second tier, similar to the one proposed by the ACNW, that would be used to understand what impact, if any, the less mobile radionuclides might have on meeting the 10 CFR 61.41 performance objective. Also in NUREG-1573, the staff responded to public questions concerning their preference for a 10,000-year period of performance (See NUREG-1573, pp. B-16 – B-20).

Context for Selection of a Period of Performance

The NRC low-level waste disposal regulations do not specify a period of performance. However, the documentation supporting the environmental impact statement 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[3], the analysis framework (assumed scenarios, receptors, and pathways), societal uncertainties, and uncertainty in predicting the behavior of natural systems over time. Both technical (e.g., the characteristics and persistence of the radiological hazard attributed to the waste) and socioeconomic (e.g., trans-generational equity) factors need to be considered (NEA 1995; ICRP 2000). Selection of a period of performance for low-level waste disposal should consider a number of factors. The approach provided below attempts to strike a practical

[3] The appendix to this document provides an evaluation of the how doses may vary from unit concentrations at the land surface of different material types.

balance, recognizing different sources of uncertainty and the objective of regulatory decision-making.

The purpose of completing a performance assessment of a low-level waste facility is to ensure that public health and safety is protected to prescribed limits with an acceptable degree of confidence. In NRC's terminology, that degree of confidence is described as reasonable assurance. The results of this compliance analysis are not interpreted as unequivocal numerical proof of the expected behavior of a waste disposal facility, due to the uncertainties associated with hazards and time periods involved. Uncertainties associated with the performance of natural and engineered systems may increase, and uncertainties associated with human behavior definitively increase, over extended periods of time. Uncertainty, in this context, can render the result of the calculation meaningless as input to regulatory decision-making. In the context of waste disposal, uncertainty is not a suitable reason to dispose of waste, but it may be a suitable reason to not dispose of waste if the uncertainty in the consequences is unacceptably large.

During the original development of Part 61, short-lived radionuclides were expected to dominate the radioactivity of commercial low-level waste (NRC 1981). Examination of the disposal inventory at the current operating low-level waste disposal facilities validates this expectation (Esh 2007, Chem Nuclear Systems 2005, Rood 2003). If the activity disposed of in a facility is dominated by short-lived radionuclides, the selection of a period of performance is rather straightforward: define the period of performance to include the period of maximum expected dose. However, if the activity to be disposed of has a significant fraction of long-lived radionuclides then the selection of a period of performance is not straightforward.

The characteristics of the radiological hazards associated with some waste streams, such as depleted uranium, present 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. In the case of depleted uranium, the concentration of some decay products peaks after one million years, rather than decreasing significantly over a few hundred years like that of typical low-level waste. Figure 1 provides the ratio of the activity of depleted uranium at various times to its initial activity. For comparison, a similar ratio for a commercial low-level waste facility (which includes long-lived radionuclides) is provided based on data from Barnwell, South Carolina (Chem-Nuclear Systems 2005). Commercial low-level waste can and does contain long-lived radionuclides, however the long-lived activity generally comprises a smaller fraction of the total initial activity than a waste stream such as depleted uranium. In addition to the activity, the propensity to cause dose must also be considered. Some radionuclides (including daughter products) may be transported via different mechanisms, have different mobility, or have different dose conversion factors that result in different potential dose consequences (for example, Am-241 decaying to Np-237). Whereas the activity in a commercial low-level waste facility decreases to a few percent of the initial value over a few hundred years, the activity for a waste stream such as concentrated depleted uranium would be expected to remain relatively constant initially, and begin increasing at around 1,000 years. Assuming no release from the source, peak activity would not occur until over one million years after disposal. The ratio for depleted uranium 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.

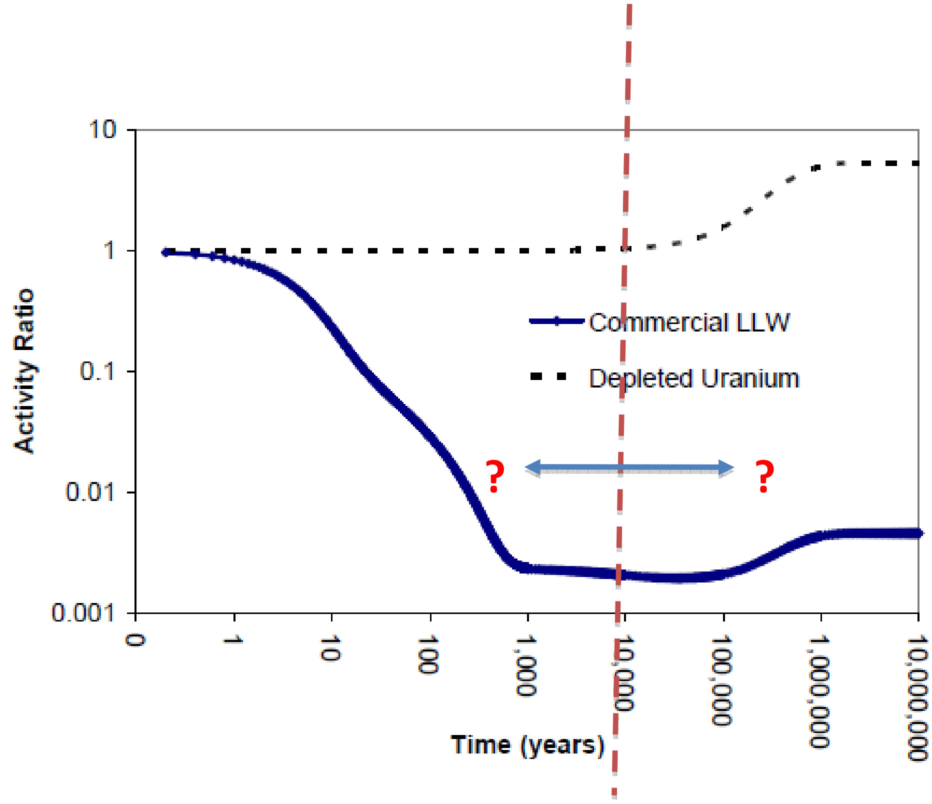


Figure 1 Activity Ratios of Depleted Uranium and Commercial Low-Level Waste (log-log plot). The dashed vertical line represents a potential selection of a period of performance in relation to the waste characteristics.

In particular, the activity of ^{222}Rn and ^{210}Pb increase by more than a factor of 1,000 between one thousand years and one million years after disposal. Because different elements can have different mobility and radiotoxicity, total activity may not directly translate to risk (dose). Presenting the information on a linear scale for a daughter radionuclide may result in a different perspective. Figure 2 provides the concentration of ^{226}Ra in a waste disposal facility containing depleted uranium. The concentration of ^{226}Ra is approximately thirty times less at 10,000 years than at one million years. Identified on the figure is the 10,000 year period of performance recommended by the performance assessment working group in NUREG-1573 for typical commercial low-level waste. As a result of these characteristics of the source term, assessment of the risk of waste streams such as depleted uranium disposed of in the near-surface may require an evaluation of a number of different features, events, and processes over long timeframes. However, other waste streams that may be considered for disposal in the near surface may not have characteristics similar to depleted uranium. For instance, blended wastes could be comprised of mostly short-lived radionuclides; the period of performance that may be appropriate could be strongly influenced by the characteristics of the waste stream.

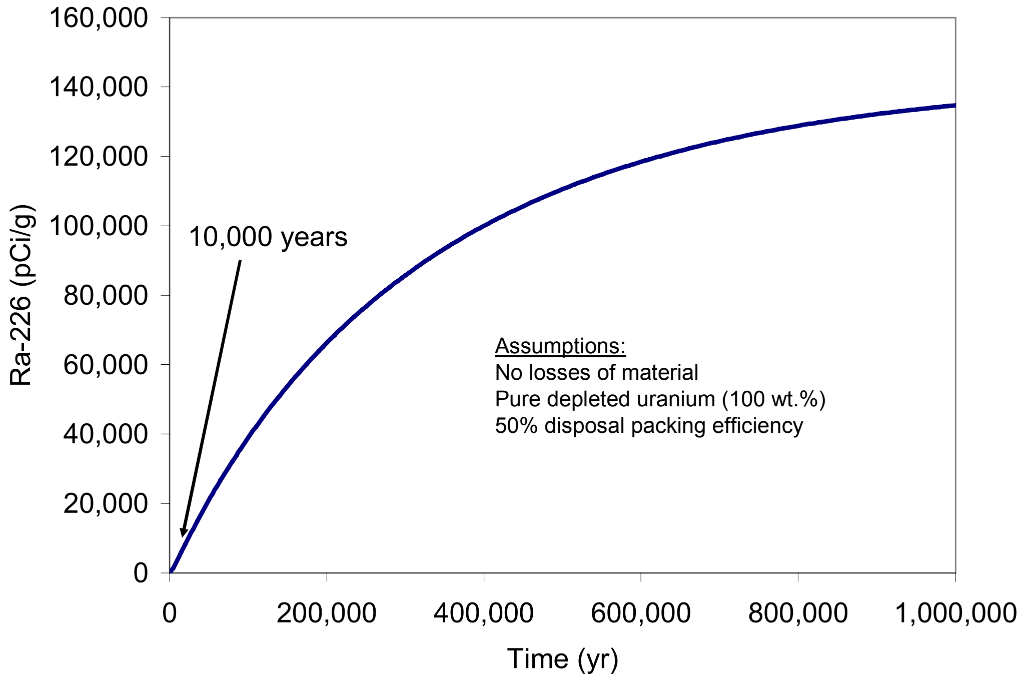


Figure 2 ^{226}Ra Concentration in a Hypothetical Low-Level Waste Disposal Facility Resulting from Disposal of a Concentrated Depleted Uranium Waste Stream.

Performance assessments are used to understand how a system (e.g. disposal facility and natural environment) may perform. They are used to understand the potential impacts of uncertainties, which need to be considered by decision makers. Figure 3 is a conceptual representation of the types of uncertainties inherent in evaluating the disposal of radioactive wastes. Some of these uncertainties are explicitly considered in performance assessments whereas others are not. There are numerous sources of uncertainty associated with projecting the future risks from disposal including, but not limited to, natural, engineering, and societal sources. Figure 3 is used to illustrate that the uncertainties are not likely to be constant and that their relative ratios could be drastically different.

The staff used its experience with waste disposal systems to generate Figure 3. Figure 3 is only intended to illustrate concepts associated with uncertainties affecting waste disposal; it is not a quantitative representation of the long-term uncertainty of the consequences of waste disposal. Uncertainties are shown as distributions in the individual component figures (3a, 3b, 3c) and in the small composite figure (3d). Figure 4 is a larger composite figure, which shows the types of processes or considerations that may impact long-term uncertainties. Uncertainties are shown as single values for clarity, but would more appropriately be reflected as distributions of values (as shown in Figure 3). Further, the shapes of the curves may change for specific sites, designs, and applications[4].

[4] The curves generated here result from staff experience completing and reviewing performance assessments for a variety of sites. The relative uncertainty should not be confused with risk as large uncertainties can impact decision metrics both favorably and negatively. However, relative uncertainty does affect the meaningfulness of the results and should affect the level of confidence placed in the results. Large relative uncertainties suggest less confidence should be placed in the results of calculations.

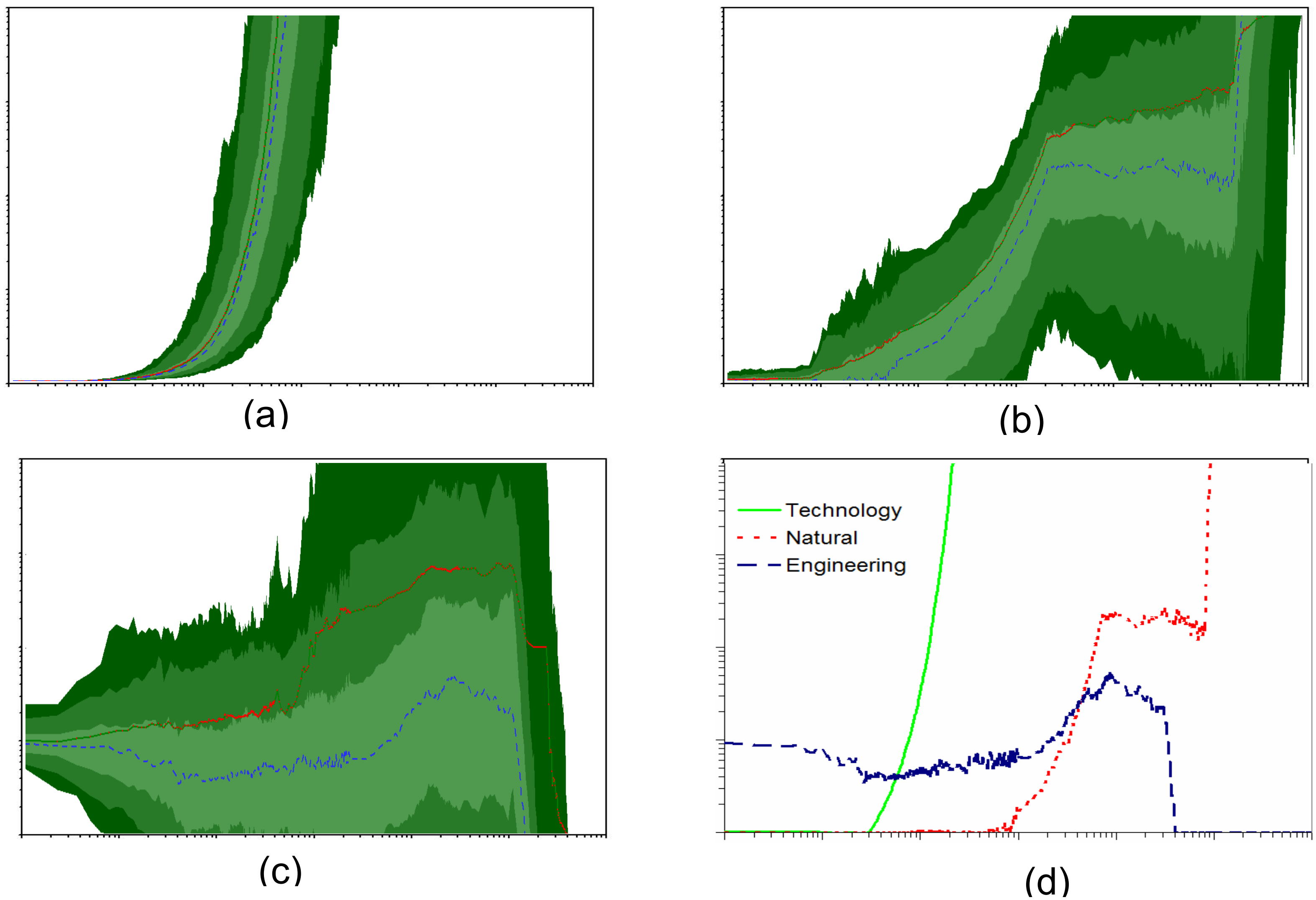


Figure 3 Types of Uncertainties in the Near-Surface Disposal of Radioactive Waste and their Relative Magnitudes. (a) Societal components, (b) Natural components, (c) Engineering components, (d) All components

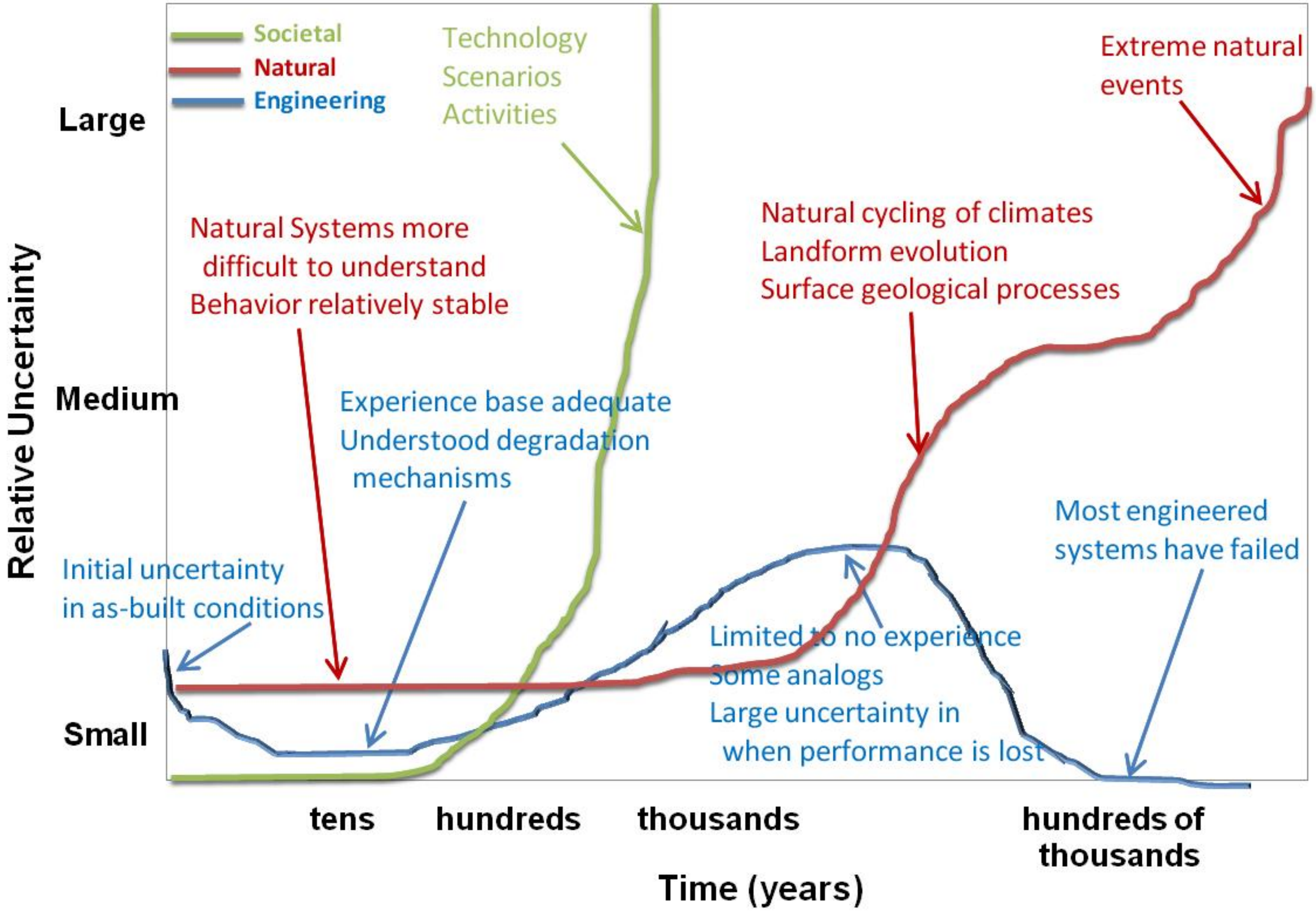


Figure 4 Types of Uncertainties and their Relative Magnitudes in the Near-Surface Disposal of Radioactive Waste with Explanation of Contributing Processes and Events. Figure is a conceptual representation, not quantitative.

The main features that Figures 3 and 4 are intended to convey are:

- The relative impact of uncertainty of a particular type can be dynamic.
- Different types of uncertainty may dominate the system response at different times.
- If technology development is considered, societal uncertainties are likely to dominate other sources of uncertainty.

Although it may be difficult to quantify societal uncertainties, which in this context have been described to have major components of technology development, scenarios, and future activities, the technology development component of uncertainty has been large over recorded history. The large volatility of societal uncertainty does not necessarily mean that the changes have been positive. Societies can go through periods where standards of living may decrease and knowledge may be effectively lost or progress may be halted. If this were to occur, the relative risk from past waste disposal would effectively decrease. In terms of development and deployment of technologies to identify, characterize, and remediate environmental hazards, the growth rate has been exponential (and positive) over the last several hundred years. The technologies that are employed today, in many cases, did not exist one hundred years ago. The rate of development and adoption of risk mitigation technologies can be recognized by considering the difference existing today between developed and undeveloped countries. Developed countries maintain strict standards for limiting public exposure to environmental contaminants whereas undeveloped countries struggle to provide basic necessities such as safe water.

Natural system uncertainties may be less volatile in the near- and not-too-distant-future relative to societal uncertainties. Some natural system processes, such as geochemical processes that determine radionuclide transport, may be relatively stable and sufficiently understood so that predictions for the long-term may be relatively robust. Natural analogs have been used to provide understanding over very long timeframes. Other natural system processes, such as geomorphology, may be considerably more dynamic and our experience base of observations and relevant analogs is more limited. Much research has been conducted to understand what has happened in a particular area or to a landform, but that research does not readily translate into what will happen in the future at a particular site. After many thousand years and longer, natural system uncertainties are likely to increase and at some point become sufficiently large to limit the usefulness of predictions and calculations. Deeper disposal, including geologic disposal, is typically used to mitigate the natural system uncertainties such as geomorphological processes associated with long timeframes.

The selection of a period of performance or an approach to period of performance for the evaluation of the disposal of low-level waste streams should consider the sources of uncertainty and how they may impact projected future risk. The uncertainties will influence how those projected future risks should be interpreted. Although individual components of uncertainty may increase or decrease, the overall uncertainty generally increases with time.

The National Academy of Public Administration (NAPA) recognized that intergenerational decision-making involves a number of variables (NAPA 1997). According to NAPA, each generation must consider not only how its actions will affect future generations, but also how inaction will impact the current generation and may negatively affect future generations. NAPA outlined four basic principles:

1) Every generation has obligations as trustee to protect the interests of future generations.

2) No generation should deprive future generations of the opportunity of a quality of life comparable to its own.
3) Each generation's primary obligation is to provide for the needs of the living and succeeding generations. Near-term concrete hazards have priority over long-term hypothetical hazards.
4) Actions that pose a realistic threat of irreversible harm or catastrophic consequences should not be pursued unless there is some countervailing need to benefit either current of future generations.

The potential environmental impacts from the disposal of low-level waste may extend from the current generation to future generations. The NRC has not formally adopted NAPA's principles, though the concepts associated with them are found throughout various NRC regulatory programs. The principles established by the NAPA have been retained or modified slightly for application to the very long timeframes that could be applied to radioactive waste disposal, as will be discussed in the recommendation section of this paper.

Options Considered

A variety of approaches have been considered in this paper for selection of the period of performance for the assessment of low-level waste disposal. These approaches are summarized below. Some of the considerations discussed are subjective and are based on staff experiences and opinions. Selection of a period of performance is a policy decision that constrains regulatory decision-making. An appropriate period of performance is generally not something that is readily quantifiable. The diverse set of decision variables and numerous uncertainties makes quantification of a period of performance difficult if not impossible. Most stakeholders will likely agree that certain values are clearly unreasonable (e.g., 10 years [too short] or one billion years [too long]). The challenge arises when considering intermediate values. The diversity of opinions results from the different weights assigned to different decision variables.

<u>Option 1—No Change from Current Approach</u>

A period of performance is not specified in 10 CFR Part 61 for assessment of the performance objectives. Licensees use different periods of time to evaluate their disposal facilities' performance. Periods of performance have ranged from 500 years to peak dose (Wilhite 2003, WCS 2004, DOH 2004, UDEQ 2001). In guidance, NRC staff communicated that in most cases a period of 10,000 years would be sufficient to capture the risk from most long-lived relatively mobile radionuclides and to provide an understanding of disposal facility performance (NRC 2000).

The major disadvantage associated with this approach is that without a specified period of performance, there is ambiguity in how a period of performance should be selected and how to apply it to different sections of the regulations. There is no strong regulatory mechanism to prevent an inappropriate selection of a period of performance. During the workshops NRC held in September 2009, most of the participants argued that the selection of period of performance was a policy decision, and that the policy should be consistent across the national low-level waste program; most stakeholders felt a period of performance or approach to period of performance should be specified in the regulations (NRC 2009a, NRC 2009b). Although the participants supported a consistent period of performance, many different values for the period of performance were proposed. Some stakeholders expressed concern that if the period of performance was too long, disposal facilities would not be licensed because the disposal facilities could not be modeled for those timeframes. Other stakeholders expressed concern that if the period of performance was too short, risks from disposal would be not be properly assessed and inappropriate decisions could be made. The main advantage of the current approach is that it allows the Agreement States to select a period of performance consistent with State policies. But this approach also results in different periods of performance from state-to-state, which could cause confusion among licensees that have to send low-level waste to disposal sites in different states.

<u>Option 2—Peak Dose</u>

Some stakeholders advocate selecting a period of performance to ensure the peak dose is captured regardless of when it occurs. This approach, if regulatory limits are met, ensures future generations are provided with the same level of protection as the current generation. The stakeholders believe that the present generation should be responsible for the problems they have created without burdening future generations. Addressing these intergenerational equity concerns is the primary advantage of a period of performance consistent with peak dose. A secondary advantage is that it may be perceived as being easier for decision makers to justify a decision because they can point to the results of a calculation.

However this approach does have disadvantages.

- Use of peak dose, without considering when peak dose occurs, could provide misleading information and false confidence to decision makers.
- The resources required to ensure today that a future generation is protected may be much larger than the resources necessary to protect current and near-term generations.
- Use of peak dose for the disposal of long-lived radioactive waste would be inconsistent with the disposal of industrial metals or other potentially hazardous materials that may be radiologically stable and therefore have effectively an infinite half-life.
- Peak dose could occur beyond the period of geologic stability, which would render quantitative values essentially meaningless.

Just because a calculation can be performed or computer model parameters can be set to estimate results for longer periods of time does not necessarily mean that the results of the calculations have meaning. If all significant sources of uncertainty are not reflected in the calculations, the results of the calculations can imply a level of precision that is not warranted. For long periods of time, some uncertainties cannot be quantified (e.g., those associated with landform evolution).

As shown in Figure 4, there are many different types of uncertainties that can influence the projected risks. In general, performance assessments attempt to incorporate or bound the impact from uncertainties in natural and engineered system performance. For societal uncertainty, technological evolution is usually not considered because the future impact of technology development cannot be quantified. The analysis fixes other components of societal uncertainty by specifying scenarios that should be applied and prescribing the future activities of humans to avoid unproductive speculation (i.e., the analysis does not consider things that may not be known with reasonable certainty). Scenarios and the activities of future receptors[5] are frequently defined based on current practices, which are also assumed for future generations.

[5] The term 'future receptor' is used to reference a member of the public living offsite or an inadvertent intruder performing activities onsite at a future point in time.

This is not unreasonable because societies have consistently required basic necessities, such as food and shelter, even if the sources of food and the form of shelter have varied.

Over longer periods, changes in technology will occur although the exact change in technology is unknown. In other words, the uncertainty associated with the evolution of technology is known to be large, but the exact value, if it could be reduced to a value, is unknown. Changes in technology could entail the ability to identify a contaminant in the environment, the improvement in techniques to mitigate the effects of a known contaminant, and a better understanding of the impact of contaminants on humans and the environment. For example, radon gas was discovered a little over one hundred years ago; at the time of discovery, little was known about the potential health impacts from exposure to radon and there were no technologies available to mitigate those health impacts. One hundred years in the context of long-lived waste would barely be a point on a projected dose curve. In many municipalities today, homebuyers can have their home tested for radon gas and if elevated levels are found, mitigation systems can be installed. Common mitigation systems are not prohibitively expensive and are quite effective at reducing the risks from radon gas in the home. This is an example of how changes in technology can mitigate health risks; in this case, a health risk was identified and cost-effective methods to reduce the risk were developed in a relatively short period of time compared to long-lived radioactive waste. Societies can identify and mitigate environmental problems relatively efficiently, though it is rare, if not unheard of, for this capability to be a primary element in regulatory decisions.

The disposal of industrial metals and other potentially hazardous materials uses a different approach than the disposal of low-level radioactive waste. Low-level radioactive waste, because it is generated in much smaller quantities, is disposed of in facilities that are sited in locations that use the natural system to limit potential releases to the public and environment. Institutional controls may be provided for up to one hundred years to ensure the facility is stable, the engineered system is performing as intended, and monitoring and maintenance can be performed. Low-level waste disposal considers the potential for inadvertent intrusion into the waste, and waste concentrations may be limited as a result.

Industrial metals and hazardous wastes are generated in much larger quantities, which caused the Environmental Protection Agency to develop a prescriptive design-based approach using engineered barriers to prevent releases of the materials to the environment. Hazardous waste facilities are monitored and maintained for thirty years, at which time the land can be released (if appropriate) or the facilities can be monitored and maintained for a longer period of time. Inadvertent intrusion into the facility is not considered. It could be inconsistent and overly restrictive to impose a peak dose metric for disposal of long-lived low-level waste if similar metrics are not applied to other activities, such as disposal of hazardous waste that can result in long-term impacts to human health and the environment.

Option 3—Regulatory Precedent

The staff has reviewed various approaches for the period of performance under several NRC regulations. The staff has also considered approaches used by some international programs. This section summarizes current NRC regulatory approaches to the period of performance in waste management as well as international experience. Other NRC waste management programs that use a period of performance include decommissioning, high-level waste (HLW) disposal, and management of mill tailings (10 CFR Parts 20, 40, 60, and 63).

Subpart E of 10 CFR Part 20 requires that the analysis for decommissioning of sites determine the peak annual TEDE dose within the first one thousand years after decommissioning. However, at most facilities undergoing decommissioning, the quantity of long-lived radionuclides of concern is 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. This is a very important point: it is not just the value of the period of performance that determines safety, but the associated assumptions and corresponding regulatory framework (including technical analysis and the specified period of performance) that provides for protection of public health and safety. Because direct (inadvertent) access to the contamination is assumed to occur at these facilities undergoing decommissioning, the risk from long-lived radionuclides that may have long environmental transport times is mostly captured with the 1,000-year period of performance. The dose after 1,000 years could be larger when the groundwater pathway primarily drives the dose and sorption is moderate or high, or when daughter radionuclides have been separated by industrial processing from parents, leading to the eventual in-growth of daughters.

The period of performance for geologic disposal of high-level nuclear waste is based on a number of considerations: (1) sufficient period of time to ensure safety of humans and the environment for the release of radiation following loss of integrity of engineered barriers; (2) adequate time to incorporate significant processes and events that impose greatest risk; (3) restricted period during which uncertainties can be prescribed with reasonable assurance; and (4) sufficient time to ensure 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. The compliance period for Yucca Mountain was specified in EPA's standard (40 CFR Part 197) at 10,000 years. But the Court of Appeals for the DC Circuit vacated the EPA's 10,000 year compliance period because it was not "'based upon and consistent with' the findings and recommendations of the National Academy of Sciences," (NAS 1995) as required by section 801 of the Energy Policy Act of 1992 (42 USC § 10141 note) *Nuclear Energy Institute v. Environmental Protection Agency,* 373 F.3d 1251, 1257 (2004). The NAS stated that compliance assessment is feasible for most physical and geologic aspects of repository performance on the time scale of one 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 developed 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 new standard for Yucca Mountain uses a tiered approach. For the first 10,000 years, the dose to the Reasonably Maximally Exposed Individual (RMEI) must not exceed 150 μSv/yr (15 mrem/yr) total effective dose equivalent (TEDE). Originally, from the period after 10,000 years extending to one million years after closure the EPA proposed that the dose was not to exceed 3.5 mSv/yr (350 mrem/yr) (EPA 2005). In the final standard, the dose limit applicable to the period from 10,000 years to one million years was set at 1 mSv/yr (100 mrem/yr). The EPA, in the Federal Register Notice for the proposed revision of 40 CFR Part 197, provided a discussion of many of the considerations found in this paper with respect to the disposal of long-lived high-level radioactive waste (EPA 2005). Yucca Mountain is the only precedent in the U.S. for the disposal of radioactive materials where the consideration of effects extending potentially to one million years is required. NRC implemented the EPA standards in 10 CFR Part 63 (NRC 2009).

The standards for the management of uranium mill tailings in 10 CFR Part 40, Appendix A, require disposal in accordance with a design that provides reasonable assurance of control of radiological hazards for 1,000 years, to the extent reasonably achievable, 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 depleted uranium 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 depleted uranium will be much higher than in mill tailings as the progeny approach the same concentration as the uranium, which is much higher in depleted uranium than in mill tailings.

In development of 40 CFR Part 191, EPA proposed environmental standards for the management and disposal of spent nuclear fuel, high-level and transuranic radioactive waste. Though not an NRC regulated facility, the Waste Isolation Pilot Plant (WIPP), used for disposal of transuranic waste, is somewhat analogous to the NRC-regulated activities discussed above. WIPP was authorized under 40 CFR Part 191. In proposing and finalizing the regulation, EPA set containment requirements for 10,000 years (EPA 1982, EPA 1985). Ten thousand years was selected because it was believed that some aspects of the future could be reasonably predicted to allow for comparison and selection of disposal methods. EPA also believed that a geologic disposal system working for 10,000 years will continue to protect people and the environment beyond 10,000 years. A period of 10,000 years was long enough to ensure that groundwater impacts would most likely be realized, and that major geologic changes would not occur. Thus the system would be reasonably predictable.

Internationally there is no consensus on the approaches used for period of performance (NEA 2002, NEA 1995, NEA 2005). Many agencies and other stakeholders, as discussed below, have acknowledged the uncertainties associated with very long timeframes and have cautioned against applying quantitative standards. For example, the International Atomic Energy Agency (IAEA) noted that care has to be exercised in applying criteria for periods where uncertainties become so large that the criteria may no longer serve as a reasonable basis for decision-making (IAEA 2006). The Nuclear Energy Agency (NEA) expressed a similar concern that uncertainties can become so large that meaningful predictions regarding evolution of the systems cannot be made (NEA 2005). Most groups readily acknowledge that the results of analysis of long-term performance should not be interpreted as accurate predictions of the systems. These problems cannot be solved in the traditional sense of the word, but that doesn't mean that long-term risks shouldn't be projected and can't provide input into regulatory decision-making. Projections of disposal system performance over very long timeframes provide indicators of performance. Ultimately regulatory judgment must be used to evaluate the uncertainties associated with the timeframes involved. The ACNW provided a summary of the then current approaches to defining a time span of regulatory compliance used in many international programs (Ryan 2005). International groups, including the IAEA and NEA, have advocated some version of a tiered approach for evaluating the impact of radioactive waste disposal.

Many countries consider a multi-step approach, either explicitly or implicitly, with early and longer assessment periods. Some countries do not specify a time of compliance. For the proposed revision of 40 CFR Part 197, EPA provided a summary of a number of international approaches (See FRN Vol. 70, No.161, 49030).

The main advantage of using historical precedents from analogous NRC waste management programs is that the precedent provides a familiar and established framework to make regulatory decisions. These approaches have been successfully used in a variety of programs and activities. Considerable resources were expended in the development of the regulations, and they were vetted with a diverse group of stakeholders. The regulations, such as approaches to specifying a period of performance, have considerable value and a technical basis. The common characteristic of the existing regulations is that they were tailored for the characteristics of the waste *and the associated regulatory analyses*. The different approaches ensure public health and safety is protected for the applications they are applied to. The main disadvantage of setting a period of performance for unique waste streams based on regulatory precedent is the dissimilarity of the radioactive wastes considered in the other programs. If the wastes in the other programs aren't sufficiently analogous to the current wastes, then the use of an existing approach may not be appropriate and may not ensure protection of public health and safety. As seen in Figure 1, some waste streams may have characteristics that are substantially different from other waste streams. The approach selected for low-level waste disposal facilities must be evaluated on its own merits, in addition to satisfying regulatory precedent.

Option 4—Uncertainty Informed Approach

This option is a risk-informed, balanced approach that provides a framework for regulatory decision-making that considers significant sources of uncertainty—an uncertainty informed framework. An uncertainty informed framework for selecting the period of performance provides decision points and regulatory limits that are set considering major sources of uncertainty. The framework is divided into three timeframes: Compliance period, Assessment period, and Performance period (CAP).

Compliance period—The period of time over which the disposal facility performance can be estimated quantitatively with relatively high precision. Societal uncertainties, though large, do not prevent the performance calculations from providing meaningful information.

Assessment period—The period of time after the compliance period where performance of the disposal facility should be assessed semi-quantitatively considering uncertainties in natural and engineered system components. The assessment period is used to evaluate the relative performance of natural and engineered barriers. Societal uncertainties significantly influence the results.

Performance period—The period of time after the assessment period where performance of the disposal facility should be evaluated qualitatively. Numerous sources of uncertainty may significantly influence the results.

The objective of the CAP approach is to balance the need to consider risks to future generations, even over long periods of time, with the uncertainties that can impact the risk calculations. Figure 5(a) provides the main elements of the framework, overlain on the common radiological behavior of different types of waste streams. In addition, the principles of intergenerational decision-making are reflected in Figure 5(b).

As shown in Figure 5(a), the analysis framework for typical commercial low-level waste disposal ensures protection during the period of highest activity. The institutional control period and waste classification system (with intruder protection requirements) ensure public health and safety is protected and provide defense in depth. Because the activity drops off rapidly, a time of compliance of 1,000 years, or at sites with more sorption and slower groundwater transport a time of compliance of 10,000 years, is more than sufficient to capture the risk from long-lived and relatively mobile radionuclides. However, for waste streams such as concentrated depleted uranium, the maximum risk may not occur until much longer. Changes to the analysis framework can be considered accordingly, however management of very long-term risks is a policy decision. The approach outlined here is one alternative to managing the long-term risks that considers the uncertainties involved. If a waste stream is similar to depleted uranium (e.g. very long-lived, in-growth of more mobile daughter radionuclides), the CAP approach is one way to ensure that the long-term risks are incorporated into decision-making. The CAP approach adds additional assessment requirements, which are reflected in an assessment period and a performance period. The purpose of the tiered approach is to ensure that the potential long-term risks are communicated to decision-makers while properly reflecting the uncertainties associated with the calculations.

Figure 5(b) shows an example of dose limits and transition times for application of the CAP approach. If the CAP approach were adopted, the particular dose limits and time periods should be established in the rulemaking process. This approach attempts to balance the desire to consider long-term risks with the large and potentially increasing uncertainties over time. This approach would need to consider the following elements:

1) When should the approach be applied?

   The approach should not apply to traditional low-level waste streams with limited concentrations of long-lived radionuclides. The regulations would need to include criteria to define when the traditional approach or CAP approach should be used.

2) What is the duration of the compliance period and the associated dose limit?

   The purpose of the compliance period is to quantitatively assess the performance of the disposal facility and ensure that public health and safety is protected. Approaches such as that outlined in NUREG-1573 (10,000 years, 25 mrem/yr TEDE) and recent staff guidance may be appropriate. However, it may also be appropriate to shorten the compliance period to 5,000 years.

   Shortening the compliance period would ensure the impacts from natural climate cycling (e.g. glacier formation) are evaluated in the assessment period. If ice ages were to occur, the impacts to society (e.g. risks) from the natural processes associated with the ice ages would be severe. The release of radioactivity from waste disposal facilities would likely not have high priority if the basic necessities such as food and shelter are not being met. Providing the evaluation of climate cycling in the assessment period would ensure the evaluation, which is expected to be semi-quantitative, is consistent with the increased level of uncertainty. In addition, changes in technology over 5,000 years would be expected to be quite large. The longer the compliance time, the greater the likelihood that the calculations performed using current assumptions may be misleading to decision makers.

3) What is the duration of the assessment period and the associated dose limit, if any?

The purpose of the assessment period is to develop confidence that the long-term risks resulting from events and processes associated with natural and engineered systems that may impact a facility are assessed. The assessment period would stretch from the end of the compliance period to the beginning of the performance period. The period could be sufficiently long to include most near-surface processes and events that may affect disposal facility stability and waste release. This would ensure that the current generation attempts to develop and site facilities that provide adequate protection to future generations using available technology. The end of the assessment period and beginning of the performance period could consider uncertainty in very-long time extreme events. Over very long times, the risk of extreme events impacting society become more significant. Setting the end of the assessment period at a few hundred thousand years would ensure that the peak risk for almost all waste disposal problems would be recognized.

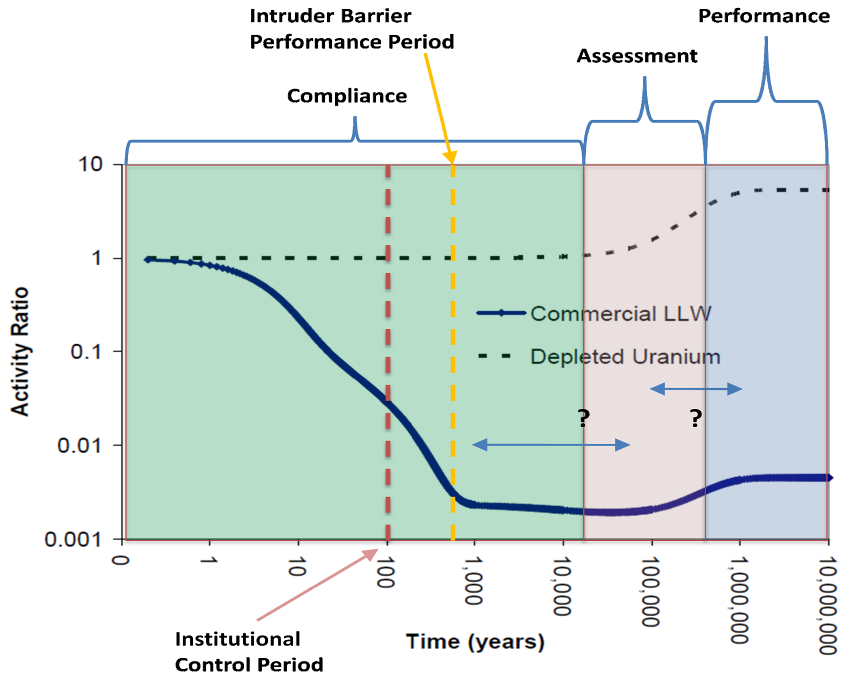
Dose limits could be omitted, or the assessment period may have a dose limit applied. Dose limits that could be considered may include the public dose limit (100 mrem/yr), a higher value consistent with background radiation and assumed radiation risks (~300 mrem/yr), or values consistent with IAEA Safety Standards for various activities (1000 mrem for the generic reference level for site remediation). In the proposed rule for Yucca Mountain, EPA considered approaches such as the difference between background radiation in different States (EPA 2005). Doses could be calculated and communicated to decision-makers who would then evaluate the impacts relative to other impacts in site environmental evaluations.

4) What is the beginning of the performance period and the associated dose limit, if any?

   The purpose of the performance period would be to communicate stylized calculation results or qualitative arguments about the relative risk of the disposal facility at very long times. The performance period would be used to ensure that at very long times the impact of the disposal facility would not be catastrophic. Application of qualitative arguments, and if desired a higher dose limit or other decision metric, would provide that hypothetical peak results are communicated. It would also provide that hypothetical peak results are considered in an appropriate context that considers the risks from other events to society, which are likely to be more significant and numerous and not reflected in the calculations.

The CAP approach attempts to reflect the principles of intergenerational decision making. First, (shown by A in Figure 5), more weight is placed on near-term hazards. Second, imposition of a requirement to assess performance in semi-quantitative or qualitative terms will ensure no catastrophic impacts to future generations (shown by B in Figure 5). Third, although not intuitive, the approach represents a comparable investment of resources for protection of current, future, and very distant future generations (shown by C in Figure 5). If a constant limit were applied for all time, the cost of protecting future generations would be much larger than protecting the current generation because of increasing uncertainties. Increasing uncertainties would ensure that more present resources would be needed to achieve the same level of confidence in far distant impacts as limiting the more near-term impacts. A tiered-dose-limit approach would allow future societies to choose which problems they want to solve and how to solve them (shown by D).

(a)



(b)

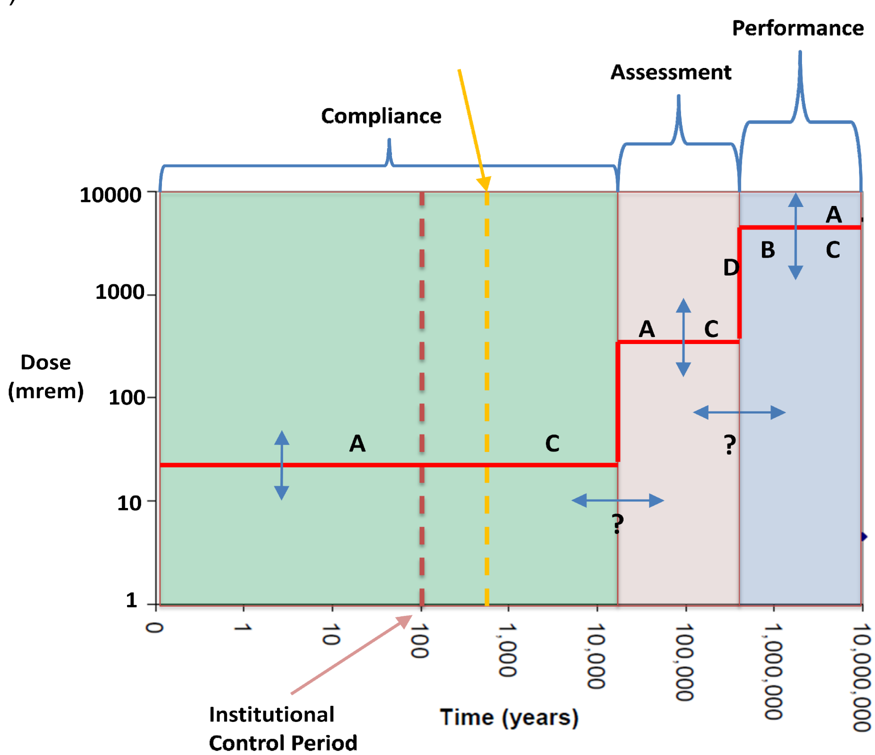


Figure 5 (a) Traditional LLW Analysis Framework and CAP Framework Compared to Traditional and Unique Waste Streams Activity, (b) CAP Framework Reflecting Timeframe Boundaries and Dose Limits. Also shown are intergenerational decision-making principles [(A) Near-term precedent over long-term, (B) No catastrophic long-term impacts, (C) Equal investment in protection, (D) Actions today shouldn't limit future decisions].

The uncertainty-informed framework has the advantage of readily attempting to work with the uncertainty inherent in evaluating the long-term risks from radioactive waste disposal. It balances the principles of protecting the health of current and future generations with the socioeconomic reality associated with allocating limited current resources. Different evaluation periods with varied expectations for the degree of quantification of the analysis are consistent with the expectation of increasing uncertainty. Tiered dose limits are also consistent with increasing uncertainty. The primary disadvantage is that the approach is a significant deviation from what has been done in the past for low-level waste in the United States. The uncertainty-informed framework would require development and specification of a variety of time periods and dose limits. The public could also view this approach as providing less protection for future generations if tiered dose limits were applied, and the resource utilization and uncertainty context was misunderstood.

Option 5—Other Industrial Metals Approach

EPA regulations for hazardous waste disposal facilities specify detailed design and waste form requirements, as well as requirements for post-closure institutional controls such as maintenance and monitoring. The regulations specify that post-closure care must begin after closure of the unit is completed and continue for at least 30 years. The post-closure care period can be extended to protect public health and the environment.

Very long-lived radioactive waste is not substantially different from industrial waste, such as heavy metals, which can pose significant health risks in high concentrations. And although some heavy metals can be biodegraded in the environment, the effective half-lives for most are believed to be very long (i.e. hundreds of thousands of years). The approach to managing very long-lived low-level waste could adopt continual review and reassessment (e.g. perpetual institutional control, monitoring, and maintenance), though this has not been NRC policy with respect to waste disposal.

After satisfactory disposal site closure under 10 CFR Part 61, licenses are transferred to the State or Federal government, one of which is required by the regulations to own the disposal site. Following the prescribed period of institutional control (up to 100 years), the license is terminated by the Commission. In other words, the site operator transfers the license to the disposal site owner (state or Federal government) after the disposal site closure phase. The Commission envisioned a 5-year period during which the licensee would remain at the disposal site to ensure that the site is stable and ready for institutional control. The Commission can prescribe longer periods of time to demonstrate the disposal site is stable, if warranted. However, the concept captured in Part 61 is that the involvement of a disposal site operator will follow a well-defined timeline. The more open-ended process associated with the disposal of industrial metals may be a disadvantage to adoption of this type of approach. At a minimum, adoption of an approach based on perpetual control would be a large policy shift for the Commission.

Evaluation of Options

As discussed previously, the National Academy of Public Administration recognized that intergenerational equity involves a number of variables and developed four basic principles that should apply when making decisions. Staff believes that these principles, with minor modification, are reasonable to apply to radioactive waste disposal:

(1) Every generation has an obligation to protect the interests of future generations.
(2) Future generations deserve a comparable investment of resources in protection as invested for the current generation.
(3) Each generation's primary obligation is to provide for both the needs of the current generation as well as future generations. However, near-term concrete hazards have priority over long-term hypothetical hazards.
(4) Actions that pose irreversible harm or catastrophic consequences should not be pursued.
(5) Actions today should not prevent future generations from making independent decisions.

The staff modified principle (2) and added (5) to account for the very long timeframes potentially applicable to radioactive waste disposal. Uncertainty is not unique to decision-making for radioactive waste disposal, but it is unique in terms of the very long timeframes that can be considered in waste disposal. This uncertainty can result in perverse outcomes for different groups of stakeholders (e.g., the present generation, very distant future generations) at the extremes.

Selection of a value for period of performance and associated dose limits will affect the resources needed to ensure compliance with the regulations. Imposing very strict limits, which in this case could involve a low dose limit for extremely long timeframes, would result in a very large reallocation of resources from the present generation to future generations for a risk that may not materialize or may be valued much differently by future generations. Use of a constant dose limit across all timeframes would ensure that present technology is used to mitigate a risk for a future society, which may have access to much better technology. If current technology is much less efficient at solving the problem than future technology, resources that would otherwise be available for other purposes would not be available; this requirement may have the perverse effect of increasing overall risk integrated over time and different generations. If the evolution of technology is considered, the rate of increase in dose limits or what is an appropriate amount to invest today to reduce future doses would be heavily discounted. Staff recognizes these limitations when it develops regulatory requirements that will impact safety decisions. On the other hand, selection of a period of performance that is too short may not provide adequate protection to future generations. In addition, if analysis of long-term impacts is not required, there is no incentive to mitigate the impacts. It is not possible to know with certainty what the exact future impacts will be. A policy that does not facilitate a proper allocation of resources should not be selected.

The NRC has developed a policy to inform regulatory decision-making. The NRC has applied a $2000 per person-rem conversion factor to inform regulatory decisions (NUREG-1530) and evaluate potential new regulatory requirements (NRC 1995 and NRC 2004). The conversion factor is used in regulatory analysis, such as in As Low As Reasonably Achievable (ALARA) programs. The conversion factor attempts to capture the dollar value of the health detriment resulting from radiation exposure. For example, using dollar per person-rem values and discounting to estimate present worth, even at very low discount rates, would result in the conclusion that only very small amounts should be spent today to mitigate very long term risks. In other words, very distant generations should be afforded little protection if this approach was applied to very long timeframes. Staff acknowledges that discounting is based on unstated economic assumptions that may not be valid over very long timeframes. In NUREG-1530, the authors evaluated different methods to value a statistical life to develop a dollar per person-rem factor (NRC 1995). One method looked at values implied by government expenditures. The values (in 1990 dollars) ranged from $12,000 for scoliosis and neuromuscular disease to $85,000 for regulatory and warning signs. The implied value to limit exposure in the defense high-level radioactive waste program was $490 million. There is a large range of values and the values for nuclear issues, especially nuclear waste issues, tend to be at the very high end of the range.

Table I provides the options considered in this paper and assigned ratings of qualitative decision analysis variables (defined below). The decision analysis variables were developed to reflect the technical and practical aspects of selecting and implementing a new approach to period of performance. The selection of the decision analysis variables and their ratings are based on the staff's experience and technical judgment. The ratings are assigned values of low (L), moderate (M), and high (H). Where appropriate, ranges for the variables have been provided. The decision variables and their description are:

- *Protectiveness of Public Health and Safety*—The level of protection afforded to current and future generations. A low rating does not mean that the option considered does not provide adequate protection of public health and safety (all of the options would provide adequate protection); a low rating means that on a relative basis the lower-rated option could provide less protection than other options.
- *Consistency with Intergenerational Principles*—The degree to which the option would account for the intergenerational decision making principles listed in this section. Ratings were assigned based on the ability of the option to satisfy all five principles.
- *Consistency with Current NRC Policy*—The degree of consistency with current NRC policy with respect to assignment of a period of performance in waste disposal and decommissioning activities[6].
- *Treatment of Uncertainty*—The rigor with which the option considers uncertainty. The consideration of uncertainty has technical and socioeconomic components.
- *Facilitate Regulatory Decision Making*—The degree to which the option will allow regulatory decisions to be formulated, explained, and understood.

All options provide reasonable assurance of a high level of protection for the current and near-term generations.

Table I Assessment of Decision Variables for Period of Performance Options Evaluation

Option #	Protectiveness of Public Health and Safety	Consistency with Intergenerational Principles	Consistency with Current NRC Policy	Treatment of Uncertainty	Facilitate Regulatory Decision Making
1	L to H	L to H	H	M	L to H
2	H	L to H	M	L to H	L
3	M to H	M	H	L to M	M to H
4	H	M to H	L to M	H	H
5	H	H	L	L	H

[6] The ratings assigned for Consistency with Current NRC Policy is reflective of the level of difficulty in achieving consensus with various stakeholders, both internal and external to the NRC. In general, an approach that is more consistent with current policy should better facilitate achieving consensus.
The amount of effort required to develop information to support that consensus facilitating work would be inversely proportional to the rating.

All options also would ensure current and future generations are not burdened with catastrophic consequences. The NRC would not adopt regulatory criteria that allow for catastrophic consequences. For the other decision variables, the ratings assigned vary among the options.

Option #1 is difficult to rate for a number of the decision variables. In the current approach, the period of performance is undefined in the regulations and open to interpretation. The high degree of flexibility can translate into a diverse set of ratings. For example, Option #1 was rated L to H in protectiveness of public health and safety. The protection of the current and near-term generations is high for all the options. However, with respect to protection of future generations the level of protection could vary. The period of performance could be set short, which may be appropriate for short-lived waste, but may be inappropriate for long-lived waste, depending on the concentration and quantity of waste. Likewise, if the period of performance was selected to be extremely long in the application of the licensing process, such as peak dose regardless of when the peak may occur, protectiveness would be very high, but the resources required to afford that protection may be large. Option #1 would be highly consistent with current NRC policy. The current approach does not include a formal consideration of uncertainty, though uncertainty was implicitly included in the development of the approach (see e.g., NUREG-1573).

Option #2 is highly protective of current and future generations. It is also highly consistent with many of the principles of intergenerational decision-making. For instance, the current generation is assuming responsibility for the full protection of future generations. However, it does not provide priority for near-term known hazards over long-term hypothetical hazards. Also, it could be argued that it results in a very disproportionate allocation of resources to future generations. Because uncertainties are increasing, much larger resources would likely be required for the present generation to provide future generations a constant level of protection. In an environment of unlimited resources and a single risk, that from radioactive waste disposal, Option #2 may be the most favorable option. However, resources are not unlimited and radioactive waste disposal represents one of many risks to future generations. Resources that are devoted today to mitigate a risk are not available for other uses that could have a larger net benefit. Care must be taken to ensure that resources aren't disproportionately allocated to future generations when the set of risks future generations may be exposed to, and their willingness to pay for those risks, are unknown. Current NRC policy in analogous waste disposal activities does not go to peak dose; the NRC policy makes implicit assumptions as to the value of calculations of the impacts for very long timeframes and the responsibility of the current generation to mitigate those impacts.

Option #2 may not facilitate regulatory decision-making, because the uncertainties associated with modeling processes and events hundreds of thousands of years in the future are very large. Option #2 could result in a false sense of confidence, if the uncertainties associated with calculations of effects occurring hundreds of thousands of years in the future are not understood. This option could result in an under-designed facility, because if a licensee must demonstrate that they meet the strict criteria at very long times they will have a natural tendency to dismiss or understate uncertainties to prove they meet the regulatory criteria. And over these long timeframes, proof in the ordinary sense of the word is simply not attainable. Staff acknowledges that the concerns expressed in this paragraph for Option #2 could also apply to other options, however the concerns apply most directly to very long timeframes and higher levels of protection associated with Option #2.

Option #3 is based on the use of regulatory precedent to establish the period of performance for the revision to 10 CFR Part 61. The approach recommended by the Performance Assessment Working Group in NUREG-1573 is analogous to the approach adopted in 40 CFR Part 197 for

Yucca Mountain, with the primary difference being that the standard for Yucca Mountain specifies a dose limit to apply beyond the 10,000 year compliance period and within the period of geologic stability. A dose limit of 150 μSv/yr (15 mrem/yr) was assigned for the period up to 10,000 years and a dose limit of 1 mSv/yr (100 mrem/yr) was prescribed after 10,000 years to the period of geologic stability. The approach recommended in NUREG-1573 for low-level waste disposal is to limit doses to 250 μSv/yr (25 mrem/yr) within 10,000 years following closure of the facility and to include the impacts after this timeframe in the environmental analyses for the site. Conceptually, the approaches are similar: both specify strict limits when the effects of waste disposal can be estimated with higher accuracy and both account for longer-term impacts when uncertainties are much higher and accuracy is lower. Both approaches prioritize better known near-term consequences over lesser known long-term consequences. The approach recommended in NUREG-1573 is different from that prescribed in 40 CFR Part 197 in that regulatory limits are not recommended for time periods after the compliance period. For decommissioning and the disposal of mill tailings, periods of performance are prescribed that are believed to be long enough to protect public health and safety. The characteristics of the materials combined with the regulatory analysis (e.g. receptor definition and behaviors) ensure that in most cases the peak dose to a member of the public occurs within the analysis period. Long-term impacts are not ignored; only the level of rigor with which they are evaluated changes. Option #3 is fairly well-balanced and is rated moderate to high on most metrics. Option #3 is rated lower for consideration of uncertainty because, while uncertainty is being considered, it is considered in an implicit manner in defining evaluation time periods and associated dose limits. Option #3 also could suffer from the same problems as Option #1: if the requirements are not clearly specified and the rationale for those requirements is not explained, Option #3 could afford too much flexibility. Option #3 would have high consistency with existing NRC policy, but it could be perceived as not being protective of future generations and as not appropriately representing intergenerational decision-making principles if an approach similar to that recommended in NUREG-1573 is adopted without explanation of how the requirements are achieving the goals.

The CAP approach (Option #4) may have the most value in the long-term because it best reflects the uncertainties associated with long-term assessments. The CAP approach would ensure long-term impacts are communicated to decision-makers. It would also ensure that those longer-term impacts are placed in a proper context with respect to uncertainties and the approach reflects principles of long-term decision-making. However, the primary staff concern with this approach is that there would likely be negative feedback because it represents the largest change from the current approach. The CAP approach would result in an explicit definition of time periods and dose limits for those time periods. In addition, a more formal socioeconomic evaluation could be needed to provide input into the various decision points (e.g. time phase boundaries and dose limits) and that type of evaluation would take time and resources that weren't anticipated in planning for the limited rulemaking, although this is a secondary concern.

Option #5 would adopt an approach similar to that used for industrial metals and hazardous materials. This option, with a 30 year or other appropriate evaluation period and a deferred final closure action, is highly protective of public health and safety for the current generations and near-term future generations. Active monitoring and maintenance can be highly effective at limiting releases and mitigating risks. This option is consistent with the intergenerational decision making principles: near-term hazards have precedent and resources are allocated accordingly, catastrophic consequences are prevented, and actions today will not limit the decision-making of future generations. The significant disadvantages of this option are that this approach is not consistent with current NRC policy and does not address long-term uncertainty.

The long-term limitation of exposure through institutional controls and continued monitoring and maintenance and if necessary, remediation and replacement, is not the policy that the NRC has taken in the past with respect to the disposal of radioactive wastes. A cost-benefit analysis with a formal consideration of the long timeframes and uncertainties would be recommended if the NRC wanted to adopt this policy for radioactive waste disposal.

Recommended Approach

In recommending an approach, the staff has considered a variety of factors. The staff acknowledges that there is no perfect solution and that stakeholders have a diverse set of opinions. Ultimately, the staff's judgment plays an important role in regulatory decision-making, especially when there are large uncertainties. Some approaches would be much easier to implement than others. However, the staff believes it is most appropriate to select a balanced approach regardless of the ease of implementation. Ensuring protection of the current and near-term generations is paramount, and that is achieved with any option considered here. Ideally, future generations would be protected to the same level. Because of the increasing uncertainties with long timeframes, protecting future generations at the same level as current generations would require a large reallocation of resources from the current generation to future generations. Given the limited resources available for low-level waste disposal, this does not seem prudent.

<u>The staff recommends Option #3 (regulatory precedent) for assigning a period of performance for the near-surface disposal of low-level waste</u>. In particular, staff recommends a two-tiered approach with a compliance period over which the risks from disposal of radioactive waste in the near surface are quantitatively evaluated. This approach would extend the performance assessment calculations to estimate peak annual dose to provide an indication of long-term disposal facility performance (i.e. a performance period). Staff believes a two-tiered approach will ensure that shorter-, long-, and very long-term risks are assessed and communicated to decision-makers in an appropriate uncertainty framework. Staff believes the recommended approach is consistent with the principles expressed by the ACNW (Pomeroy, 1997). Regulatory precedent has taken different approaches depending on the particular waste type and the other complimentary regulatory requirements associated with a particular waste. The Performance Assessment Working Group recommended a two-tiered approach for low-level waste disposal. More recently, a variant of that approach was adopted for high-level waste disposal at Yucca Mountain, NV though the approach could be better described as a two-phase compliance period.

The two-tiered approach to the period of performance considers the persistence of the hazard of the source, which is common to most waste disposal programs. Many programs limit assessments to the period of geologic stability; this constraint is not recommended here because near-surface disposal is not the only option for the disposition of low-level waste. If the risks are too large or the uncertainties are unmanageable, long-lived low-level waste could be disposed of in a deep geologic facility. For example, transuranic waste is disposed of in a salt formation in the Waste Isolation Pilot Plant near Carlsbad, NM. If the analysis for low-level waste disposal was limited to the period of near-surface geologic stability, a licensee could argue the period of near-surface geologic stability is very short, which would avoid communicating the long-term risks and uncertainties. The evaluation of the near-surface disposal of low-level waste should identify when disposal is appropriate and safe and when other options may need to be considered. At each of the public workshops that the NRC held to solicit input on the disposal of unique waste streams (including depleted uranium) participants were asked whether they felt a two-tiered approach would be appropriate if NRC were to prescribe a period of performance in a revision to 10 CFR Part 61. There were diverse opinions expressed by the participants; the majority supported an approach that would, either quantitatively or qualitatively, consider long-term doses (NRC 2009a, NRC 2009b).

As a starting point for the discussion, the staff recommends that the first time phase of the two-tiered approach be defined as the compliance period and the second time phase be defined as the performance period. The first phase is designed to demonstrate compliance with the performance objectives. The second phase is designed to determine the relative performance of the disposal facility. A two-tiered approach requires selection of four main elements: the compliance period, the dose limit to apply during the compliance period, the time to extend the calculations to (i.e. the performance period), and the dose limit, if any, to apply to the performance period.

The recommended elements of this approach are:

- A compliance period of no less than 20,000 years, with an annual dose limit of 25 mrem TEDE.
- A requirement to perform a calculation of peak annual dose that occurs after 20,000 years as an indicator of long-term facility performance. No dose limit would apply to this analysis.
- A requirement to provide analyses that demonstrate how the facility was designed to mitigate long-term impacts.
- Associated changes to the regulations to highlight the uncertainties associated with disposing of long-lived waste and that limitations on the disposal of those materials may be needed to properly manage the uncertainties.

It is important to note that safety is not derived by a particular number or limit, but by all of the regulatory criteria. Arguably the biggest determinant of the safety of future generations is the quality of data developed and the quality of the assessment that is performed.

The first significant decision point in developing a two-tiered approach is to define the boundary between the compliance period and the performance period. The two other times this approach has been used the end of the compliance period was determined primarily based on waste-specific technical considerations (NUREG-1573 and NUREG-1538). In NUREG-1573 the staff selected a value of 10,000 years for low-level waste because it was viewed as being long enough to capture the risk from most long-lived relatively mobile radionuclides and to provide an understanding of disposal facility performance. In NUREG-1538, staff assessed the relative hazard associated with the disposal of HLW compared to a natural ore body and determined that the relative hazards started to become comparable at around 10,000 years.

Technical considerations form the primary basis for the current recommendation. The last major ice sheet reached its maximum extent in North America approximately 20,000 years ago as part of the Pliocene-Quaternary glaciation that started approximately 2.6 million years ago. Many scientists believe within the cycles of glaciation, ice sheets have advanced and retreated on 40,000 and 100,000 year time scales. The earth is currently in a warmer and wetter period known as the Holocene interglacial, which has lasted for approximately the last 10,000 to 14,000 years. Though there is considerable uncertainty in the estimates, the duration of interglacial periods over the last few hundred thousand years have been on the order of ten to twenty five thousand years[7] (Szabo 1994; Kawamura 2010, Muhs 2002). The duration and frequency of interglacial periods has been widely studied, as a large part of societal advance has occurred after the end of the last glacial period. Changes from warmer to cooler climate states have happened relatively quickly (hundreds of years or less) or possibly more slowly (thousands of years). Currently there is debate about anthropogenic effects on the duration of interglacial periods. Staff recognizes that there is considerable uncertainty in inferring past changes from present day information.

A value of 20,000 years is recommended for the compliance period for near surface disposal of low-level waste because this period of time would result in the evaluation of the effects of one of the major stressors for near surface disposal of long-lived waste: natural cycling of climate. The ACNW noted the importance of considering deleterious surface processes impacted by climate change in performance assessment (Pomeroy, 1997). A boundary between the time phases of 10,000 years would be more likely to be in the range of transition times from the current interglacial period to the next glacial period. The ACNW previously expressed agreement with the timing of climate cycles; they indicated that although the maximum climate change is not predictable with present science, all evidence from extrapolations suggests the principal effect will occur prior to ca. 20,000 years (Pomeroy, 1996). If the boundary was set in the transition time, some sites (i.e., more Northern) may have additional technical burden placed on them solely due to the selection of the compliance period compared to other sites (i.e., more Southern). Ten thousand years may be too short of a period for the processes to occur at some sites. Sites should be selected for long-lived waste because they are inherently more robust, not because of where the boundary between time phases has been selected. Though the exact transition time is not known and is subject to considerable uncertainty, 20,000 years is more likely than 10,000 years to include the transition. Longer periods, such as 50,000 or 100,000 years, may include additional interglacial periods. However a site and facility that perform acceptably through one climate cycle, assessed in a conservative manner consistent with the uncertainties, should have similar performance through multiple climate cycles.

Additionally, 20,000 years would better capture, compared to shorter time frames, the in-growth of daughter products (e.g. Ra-226, Rn-222) from long-lived parents that can occur in some waste streams. For example, as shown in Figure 2, the in-growth of Ra-226 from uranium doesn't peak until after one million years with no loss of parent from the system. All systems will have loss, which shortens the time and decreases the magnitude of the peak from daughter products. Whereas the peak radium concentration is approximately 100 times larger than that expected at 5,000 years, it is less than 20 times larger than the hypothetical maximum at 20,000 years. When loss and dispersion from the source are considered, selection of a 20,000-year compliance period may result in the peak concentration being less than a factor of ten larger than the value recognized within the compliance period. Time frames longer than 20,000 years would better capture the in-growth of daughter radionuclides in the uranium isotope decay chains. However, the rate of increase in daughter concentrations decreases with increasing timeframes. An increase in the compliance period from 5,000 years to 50,000 years results in an increase of about 15 times in radium concentrations whereas going from 50,000 years to 100,000 years results in an increase of less than a factor of two. For comparable increases, the benefits are much less. In addition, it can't be stressed enough that the radiological characteristics of the waste are only one of many inputs into the estimation of risk from the

[7] Staff acknowledge that considerable research has been devoted to understanding past climates. A detailed reference list on this topic has not been provided, as it is readily available from a number of sources, such as the US Geological Survey.

disposal of radioactive waste. The numerous other sources of uncertainty must also be considered and they have been in the balanced approach recommended by the staff.

In addition to the considerations mentioned above, selection of the value for the compliance period can influence whether radionuclides would be expected to arrive at a potential receptor location within the compliance period or within the performance period. Staff evaluated the transport characteristics of various radionuclides for different site characteristics. Distributions of values of the depth to the water table were considered and were broadly classified as shallow (1–8 m), moderate (8–30 m), and deep (30–100 m). In addition, a range of climate types broadly classified as arid, semi-arid, and humid were defined with distributions of values for infiltration rates and liquid saturations. Sorption was considered through the use of distributions of values for the distribution coefficient based on literature values. The literature values selected represent a broad range of sites and conditions for loam soil (Sheppard and Thibault, 1990). These distribution coefficients are generally log-normally distributed with moderate to high variance.

Five representative elements (U, Pu, Np, Th, Tc; out of 41 isotopes considered) were evaluated at 10,000, 20,000 and 50,000 years to determine whether the median time of arrival at a potential receptor was likely to occur before or after those time points. Consideration of three depth categories and three climate states for five radionuclides results in 45 evaluation points. Simulations were conducted with probabilistic analysis in order to account for uncertainty and variability. About a third of the points were unaffected by selection of a 10,000 to 50,000 year compliance period because travel times were less than 10,000 years. Another third of the points were unaffected by selection of a 10,000 to 50,000 year compliance period because travel times were greater than 50,000 years. Of the remaining points, selection of 20,000 years compared to 10,000 years resulted in a moderate to significant increase in the likelihood of capturing the median breakthrough of the element for all but one of the points considered. In only one case (plutonium transport at a deep, humid site) was there an additional benefit to selecting 50,000 years compared to 20,000 years. The parameters influencing this evaluation are represented with continuous distributions that can result in broad ranges of outcomes. Staff has attempted to generalize the resultant behavior; the generalizations should not be used in site-specific regulatory decisions.

The evaluation discussed above was supplemented by consideration of the transport characteristics of a broader set of elements. Table II provides the classification of different elements into groups that would be impacted either moderately or significantly by changing the boundary for the compliance period from 10,000 to 20,000 or 50,000 years. There is a benefit to selecting 20,000 years over 10,000 years when transport characteristics are taken into consideration, but limited additional benefit to selecting 50,000 years.

Selection of 20,000 years for the compliance period for low-level waste disposal may create confusion for some stakeholders because of the original selection of 10,000 years for disposal of high-level waste at Yucca Mountain, NV. In the current version of 10 CFR Part 63, a dose limit of 0.15 mSv (15 mrem) is applied at Yucca Mountain for 10,000 years; however a dose limit is also applied after 10,000 years (1.0 mSv [100 mrem]). The approach for Yucca Mountain, NV could be considered to be a two-phase compliance determination rather than a two-tiered approach. In general, deep geologic systems are inherently more stable than shallow geologic systems, which allows for a more meaningful quantitative assessment of facility performance over long timeframes. In other words, the approach selected at Yucca Mountain has considered uncertainty and the stability of the system. Different types of low-level radioactive waste can have very different characteristics (e.g. half lives, mobility, concentrations). In addition, low-

Table II Elements Influenced by Increasing the Compliance Period from 10,000 Years[1]

Depth (Horizontal) / **Climate (Vertical)**	**Shallow**	**Moderate**	**Deep**
Arid	Se, Sn, Eu, Nb, Mn, Fe	U, Np, C, Sr, I	U, Np, C, Sr, I
Semi-arid	Pu, Ac, Co, Pa	Se, Sn, Eu, Nb, Mn, Fe	U, Np, C, Sr, I
Humid	Pu, Ac, Co, Pa, Zr, Th, Cs	Pu, Ac, Co, Pa	Tc, H, Cl, Se, Sn, Eu, Nb, Mn, Fe

[1] Ra, Pb, and Am were not influenced under any of the nine conditions

level waste is different from high-level waste. There is no reason to expect that the compliance periods for low-level waste, high-level waste, or any other type of waste would need to be or should be the same. This idea was expressed on multiple occasions by the ACNW (Pomeroy, 1997; Garrick, 2000). The boundaries between the time phases in the multi-tiered approaches that have been implemented were selected because of the specific characteristics of the waste and other associated regulatory requirements.

If the CAP approach is used, the staff would recommend a shorter compliance period so that processes such as natural cycling of climate would be evaluated in the semi-quantitative assessment period, which, considering the uncertainty is more appropriate. Without adoption of the CAP approach, the staff believes it is important that the effects of the expected processes that are known with a moderate degree of certainty are evaluated. Depending on where a facility is sited, natural cycling of climate could result in moderate to severe disruption of a disposal facility (i.e., in more northern States) and to society more generally. Including the occurrence of these processes within the compliance period would encourage the development of near-surface disposal facilities for radioactive waste in areas that are less likely to be disrupted. Long-term stability is a fundamental tenet of radioactive waste disposal. Near-surface disposal of concentrated long-lived waste comes with extra technical burdens compared to the disposal of low concentrations of long-lived waste or short-lived waste.

Based on the September 2009 workshops, the staff believes that there is a general consensus that a dose limit of 25 mrem TEDE is appropriate for the compliance period (NRC 2009a, NRC 2009b). Staff also believes that this is an appropriate dose limit for the compliance period.

The second major decision point for the two-tiered approach is what dose limit to apply, if any, for the performance period. Two options were considered for the performance period: the recommendation of the Performance Assessment Working Group in NUREG-1573, which is no formal dose limit; and an approach similar to that adopted for disposal of HLW at Yucca Mountain, which provides a dose limit. The staff believes that there are numerous uncertainties associated with estimating the long-term risks from near-surface disposal of radioactive waste. The staff prefers the approach recommended by the Performance Assessment Working Group. Aspects of near-surface disposal, such as the degree of interaction of humans with the waste after disposal, are more uncertain than for geologic disposal. The main objective of the analysis of the performance period is to demonstrate how the facility has been designed to mitigate long-term risks and to ensure those risks are put in the proper context. Because the various uncertainties are diverse and large, it may not be possible to define the risk. It should be possible for a licensee to define the range of risks, but staff believes that the range of risks could, if uncertainty were fairly represented, span a range that meets or exceeds a reasonable proposed limit (e.g. 100 or 500 mrem/yr). When the risks are less well-defined, staff believes that greater flexibility is warranted for decision-makers to place those risks in a global framework and evaluate them on a relative basis against the other sources of risk to the affected stakeholders.

The recommended approach uses additional analyses for the performance period to ensure that future generations will be protected. It is important that potential risks are identified and, if possible, designed for. It is equally important that the uncertainties associated with this type of problem are openly discussed in each action, so decision-makers can act to protect the interests of their stakeholders. The recommended approach will ensure that information is generated and that uncertainties are openly acknowledged and put in the proper context. Further, the recommended approach is a significant enhancement of the status quo; much more information will be generated under Option #3. The recommended approach will ensure that there are no catastrophic outcomes because even though a regulatory limit is not applied, it is incomprehensible that a decision could be justified when a catastrophic outcome is communicated to regulators and stakeholders.

Staff also considered a peak risk approach. Use of a peak risk metric, combined with an assumption of no improvements in technology, forces society to use current technology to mitigate a problem using technology that is likely to be very inferior and expensive with respect to future technologies. This approach can burden the current generation with expending resources on hypothetical risks that may never be realized, that future generations may more effectively mitigate, or that may not be large relative to other risks to future generations. The resources used to confront a hypothetical future problem are diverted from other productive uses in society on current problems. While approaches to protecting the safety of future generations can't rely on unknown technology advancement, regulatory approaches to period of performance should consider as many sources of uncertainty as possible and allow sufficient flexibility for reacting to those uncertainties. Staff believes the recommended approach satisfies that goal.

Purely from a technical standpoint staff would have recommended the CAP approach (Option #4) over the two-tiered approach derived from the regulatory basis (Option #3). The CAP approach would set time periods and dose limits with a more formal treatment of uncertainty compared to the two-tiered approach. The CAP approach is more rigorous because uncertainty-informed limits and decision points would be defined. However, Option #4 is a large change from the current approach and could benefit from a longer period of consideration among various stakeholders prior to adoption. This paper was developed to support the Commission direction to perform a limited rulemaking in response to SECY-08-147 (NRC 2008). A future, more comprehensive evaluation of 10 CFR Part 61 is being considered under which a more substantial change to period of performance can be considered if there is enough interest from stakeholders.

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Attachment to Technical Analysis Supporting Definition of Period of Performance for Low-Level Waste Disposal

Purpose

The purpose of this analysis is to show how doses will vary with changes in the source term over time. The analysis estimates relative 1-yr-dose of various materials per unit activity concentration (mSv/yr per Bq/g or mrem/yr per pCi/g) at specific points in time. The analysis calculates a dose for a period of one year, as opposed to an annual dose that assumes a 30 or 50 year committed dose. The results provide the relative risk for different materials at different points in time. The relative risk of different materials can be used to inform the development of an approach to period of performance.

Model and Exposure Scenario

The analysis employs the RESRAD Version 6.4 code (C. Yu, 2001). RESRAD is a computer model code designed to estimate radiation doses and risks from residual radioactive materials, developed by Argonne National Laboratory (ANL). The NONNUC template file contains default probabilistic distributions for non-radionuclide specific dependent parameters and can be downloaded with the code for free. This template is used to provide input to the code to find the dose to a hypothetical person exposed for one year to contaminated material at the surface (no cover) in a contaminated zone of 10,000 m^2 and 2 m deep. (Dimensions for area and depth of the contaminated zone are the default values for the RESRAD NONNUCL.TEM template.)

The dose from the contaminated material at the surface is due to direct gamma radiation, inhalation, soil ingestion, plant ingestion, and radon. Because the scenario does not consider contamination that travels through the subsurface to the groundwater over longer periods of time, exposure due to drinking groundwater, irrigation with contaminated water, or ingestion of aquatic food is not included in these results. The benefits of this approach are that it allows one to compare risks captured by various periods of performance without having to make assumptions regarding how the contaminants are transported to the groundwater, or how a specific intrusion action may alter the activity concentration in the buried material. The differences in dose are solely attributed to the change in source term due to radioactive decay and in-growth over time.

Source Term Assumptions

The following types of materials are analyzed:

- Natural Uranium
- Depleted Uranium (DU)
- Enriched Uranium 3.5%
- Am-241
- Ra-226

The 1-yr dose is calculated at the following time periods (yrs):

- 100
- 500
- 1000
- 10,000

- 100,000
- 1,000,000

The activity concentration of the source term material is generated for each time period. The activity of each material at time zero is 0.037 Bq/g (1 pCi/g). Activity concentrations of the principal and progeny radionuclides at each time period are obtained using the external source tool in MICROSHIELD Version 5, by decaying each material for the six time periods listed above (Grove, 1995-1999).

At time zero, the activity concentrations of uranium isotopes are defined in Table 1 for the following material types: Natural Uranium, Depleted Uranium, Enriched Uranium to 3.5%, 100% Am-241 and, 100% Ra-226 [0.037 Bq/g (1 pCi/g)]. The activity concentrations (in pCi/g) of the parent and daughter radionuclides for each material type at the six time periods are listed in tables in the Appendix to this document. All other input parameters are kept at their NONNUC template default value.

Results and Analysis

As specified by the NONNUC template, the model calculates 100 observations for 3 repetitions. The 300 resulting values for dose from all pathways are assembled into a cumulative distribution function in order to find the median result.

Table 2 shows the median doses at each time period for each type of material. These results are displayed graphically in Figure 1. Note that 1 pCi/g is not directly comparable to the disposed of concentration. In order to scale these resulting doses to the disposed of concentration, one would need to consider the mixing volume that occurs as the material is brought to the surface and dispersed, as well as any other waste that is entrained in the process.

The resulting doses display different behavior depending on material type:

- The median dose per unit concentration from DU exhibits an exponential increase. After about 400,000 years, the dose per unit concentration from DU surpasses the dose resulting from enriched uranium at 3.5%. At 1 million years the dose is about 8 mSv per Bq/g (30 mrem per pCi/g).

- Enriched Uranium results in a minimally increasing dose for the first 10,000 years followed by a gradual increase that peaks at approximately 100,000 yrs. At 100,000 yrs, the dose per unit concentration from Enriched Uranium is about 3 times the dose from Depleted Uranium.

- Natural Uranium contributes a practically constant dose of about 0.315 mSv per Bq/g (1 mrem per pCi/g) because the daughter products are at equilibrium from year zero.

- Ra-226 results in a dose ranging from approximately 5.4-10.8 mSv per Bq/g (20-40 mrem per pCi/g) at year 100, and generally decreases although showing some variation over time with in-growth and decay of daughter products. The Ra-226 source and its remaining daughters have decayed to zero between 10,000 and 100,000 years.

- Am-241 contributes about 0.091 mSv per Bq/g (0.3 mrem/yr per pCi/g) at year 100 which decreases by two orders of magnitude by 10,000 years, then decreases more gradually out to 1 million yrs.

Figure 2 shows the variability in results for DU, natural uranium, and enriched uranium compared to that of Am-241 at 1 million years. The variability in the results at 100,000 yrs for enriched uranium is shown since this is approximately when the peak doses occur, while results at 100 yrs of Ra-226 and Am-241 are shown because this is when they peaked in the analysis. The largest variability in dose results is from Ra-226 at 100 yrs, which is similar to the range seen from DU at 1 million years. The doses from natural uranium and Am-241 exhibited much smaller ranges on the order of 0.135 - 0.27 mSv per Bq/g (0.5 mrem to 1 mrem per pCi/g). The variation in doses is mostly due to the fraction of time assumed to be spent indoors, which is represented by a linear distribution with a range of 0 to 1. The partial rank correlation coefficient for this parameter is above 0.96 in most realizations. Other important parameters are the depth of roots in meters (UNIFORM[.3 m, 4 m]), and fruit, vegetable, and grain consumption in kg/yr (TRIANGULAR[135 kg/yr, 178 kg/yr, 318 kg/yr]). Both of these parameters exhibited partial rank correlation coefficients above 0.6.

Table 3 summarizes the typical activity concentration of uranium in soil for various conditions. The calculations in this table apply the conversion of 0.0122 Bq/g (0.33 pCi/g) U-238 for 1 ppm U-238. This is a generalized approach that does not account for the isotopic distribution, but is adequate considering that the materials are predominantly comprised of U-238. The Table 3 concentrations would need to be converted for the appropriate scenario (e.g., quantity, concentration, configuration) in order to be applied to the dose per unit concentration of material results provided in Table 2.

Figure 3 illustrates the increasing concentrations of decay products from DU. The majority of the 0.037 Bq/g (1 pCi/g) is attributable to U-238 for natural or depleted uranium at year zero, but there is significant in-growth of the daughter Rn-222 (in gaseous form) that occurs in later time periods with DU compared to the constant contribution of Rn-222 activity in natural uranium. Rn-222 in enriched uranium also increases over time, but concentration peaks somewhere between 100,000 and 1 million years. The activity contribution of U-234 in enriched uranium is higher at the outset (contributing nearly as much activity as U-238) and then decreases over time whereas the contribution of U-234 in DU and natural uranium remains constant at a lower activity level. Due to changes such as these in source term over time, estimated risks would change with differing values for a period of performance.

Comparing the dose per unit concentration results for different materials allows one to compare, on a relative basis, the differences in dose that are influenced by decay and in-growth characteristics of the different materials. For example, consider a period of performance of 20,000 years. If a disposal facility were designed to protect the inadvertent intruder such that the intruder dose were limited to 5 mSv (500 mrem) per year at 20,000 years, then the dose from depleted uranium at 1 million years to the intruder could potentially be more than 300 times the limit. If the disposal facility were designed to protect the intruder at 50,000 years to a limit of 5mSv (500 mrem), then the doses at 1 million years could potentially be 170 times greater. In contrast, if the disposed material is enriched uranium, and the intruder dose is limited to 5mSv (500 mrem) at 20,000 years, then the potential dose which the period of performance does not encompass could potentially be 55 times greater. Of course, this type of comparison assumes that each disposal facility is exactly similar with the exception of the dose limit and period of performance. The comparison only looks at the different decay characteristics and does not consider other factors such as quantity, concentration, or configuration differences in the hypothetical disposal facilities, all of which can influence dose.

While this analysis focuses on how the different materials and their unique decay and in-growth characteristics influence doses, the variability of input parameters is limited to the distributions and probabilistic parameters in the NONNUCL Template. There are several other important factors that can have a large influence on results. These factors are discussed in detail in SECY-08-0147, "Response to Commission Order CLI-05-20 Regarding Depleted Uranium" (NRC, 2008). These other important factors include the moisture state of the system, the disposal depth of the waste, the transfer factors for uranium daughter products, and the site-specific hydrologic and geochemical conditions. Since this analysis models an intruder scenario which assumes waste has already been brought to the surface, the depth of disposal is not accounted for, which can also be a significant factor in calculating exposure.

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Table 1 **Uranium Isotopic Distribution for Material Type**

	U-234	U-235	U-238
half-life (yrs)	2.45E+05	7.038E+08	4.468E+09
specific activity Bq/g	2.3135E+08	8.0372E+04	1.2660E+04
Nat U % weight	0.005%	0.711%	99.3%
Nat U % activity	48.900%	2.200%	48.9%
DU % weight	0.001%	0.200%	99.8%
DU % activity	13.963%	1.081%	85.0%
Enriched 3.5% weight	0.029%	3.500%	96.5%
Enriched 3.5% activity	81.702%	3.426%	14.9%

Table 2 Median Doses (mrem/yr per pCi/g starting concentration) at Various Time Periods

Time Period (Yrs)	*DU*	*Enriched Uranium*	*Natural Uranium*	*Am241*	*Ra 226*
100	1.19E-01	2.66E-01	1.16E+00	3.37E-01	3.62E+01
500	1.23E-01	1.31E-01	1.16E+00	1.78E-01	3.06E+01
1,000	1.33E-01	1.75E-01	1.16E+00	8.09E-02	2.47E+01
10,000	5.24E-01	2.24E+00	1.16E+00	1.78E-03	2.47E+01
20,000	7.21E-01	3.01E+00	1.16E+00	1.78E-03	0.00E+00
50,000	1.75E+00	6.71E+00	1.16E+00	2.91E-05	0.00E+00
100,000	5.64E+00	1.65E+01	1.16E+00	1.78E-03	0.00E+00
1,000,000	3.03E+01	8.40E+00	1.16E+00	1.49E-03	0.00E+00

Median Doses (mSv/yr per Bq/g starting concentration) at Various Time Periods

	DU	*Enriched*	*Natural Uranium*	*Am241*	*Ra 226*
100	3.21E-02	7.19E-02	3.15E-01	9.11E-02	9.79E+00
500	3.34E-02	3.54E-02	3.15E-01	4.81E-02	8.28E+00
1,000	3.60E-02	4.73E-02	3.15E-01	2.19E-02	6.67E+00
10,000	1.42E-01	6.06E-01	3.15E-01	4.82E-04	0.00E+00
20,000	1.95E-01	8.14E-01	3.15E-01	4.81E-04	0.00E+00
50,000	4.74E-01	1.81E+00	3.15E-01	7.87E-06	0.00E+00
100,000	1.52E+00	4.46E+00	3.15E-01	4.82E-04	0.00E+00
1,000,000	8.19E+00	2.27E+00	3.15E-01	4.03E-04	0.00E+00

Table 3 Typical Uranium Activity Concentration for Various Materials

	percent U (mostly U-238)	*ppm U*	*Bq/g*	*pCi/g*
Natural soils	0.0003	3	0.513	14
Farm fields (from fertilizer)	0.0015	15	2.564	70
Mill Tailings	0.02	200	34	924
Low-grade uranium ores, 0.01% to 0.25% U3O8, or 0.2% U	0.2	2,000	341	9,240
High-grade ores, 18-20% U308, or 17% U	17.0	170,000	29059	785,400
Concentrated DU in disposal facility, 25% mixing, 50% packing efficiency	12.5	125,000	1526	41,250

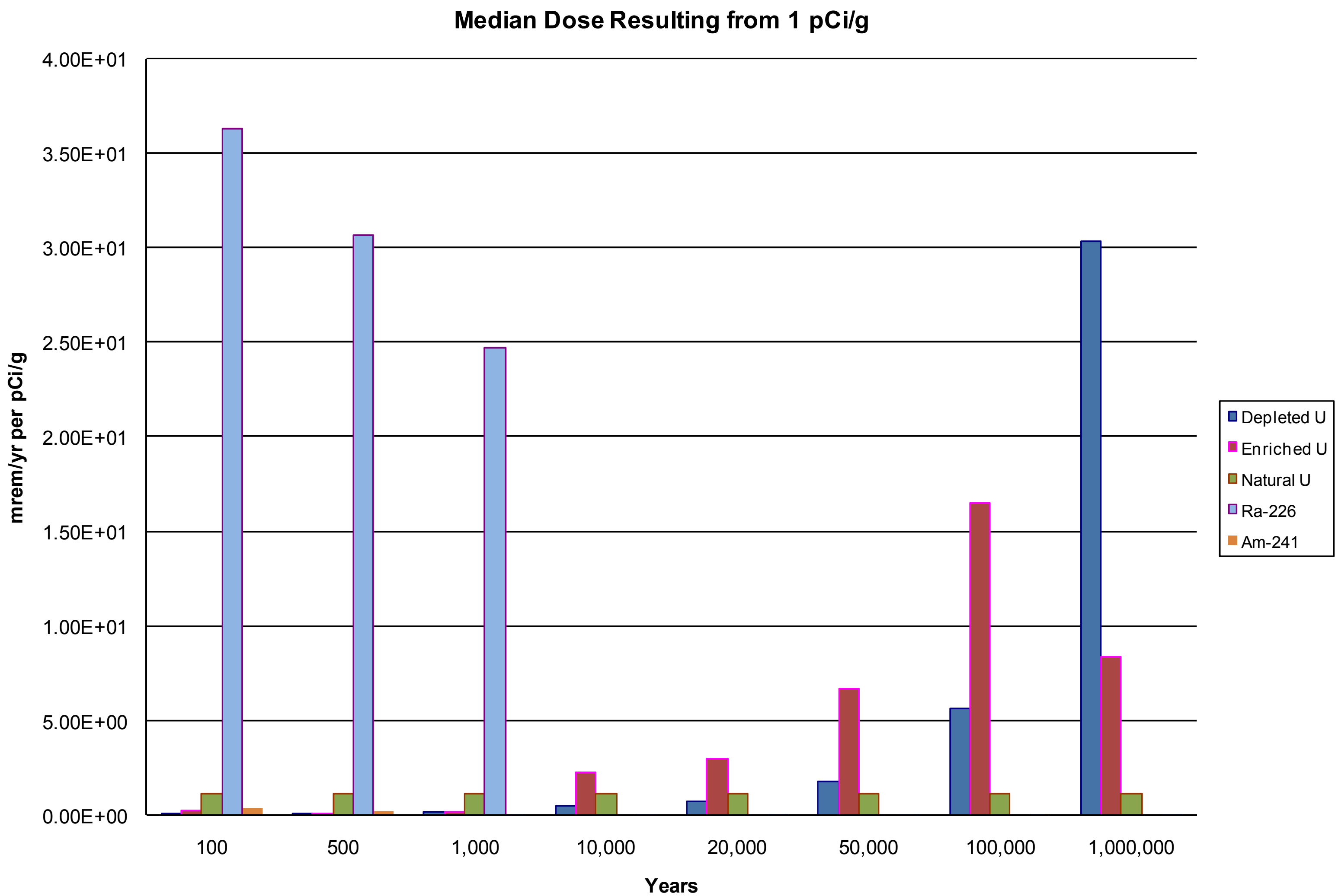

Figure 1a Median Dose at Time t resulting from 1 pCi/g of Material Type at Year Zero

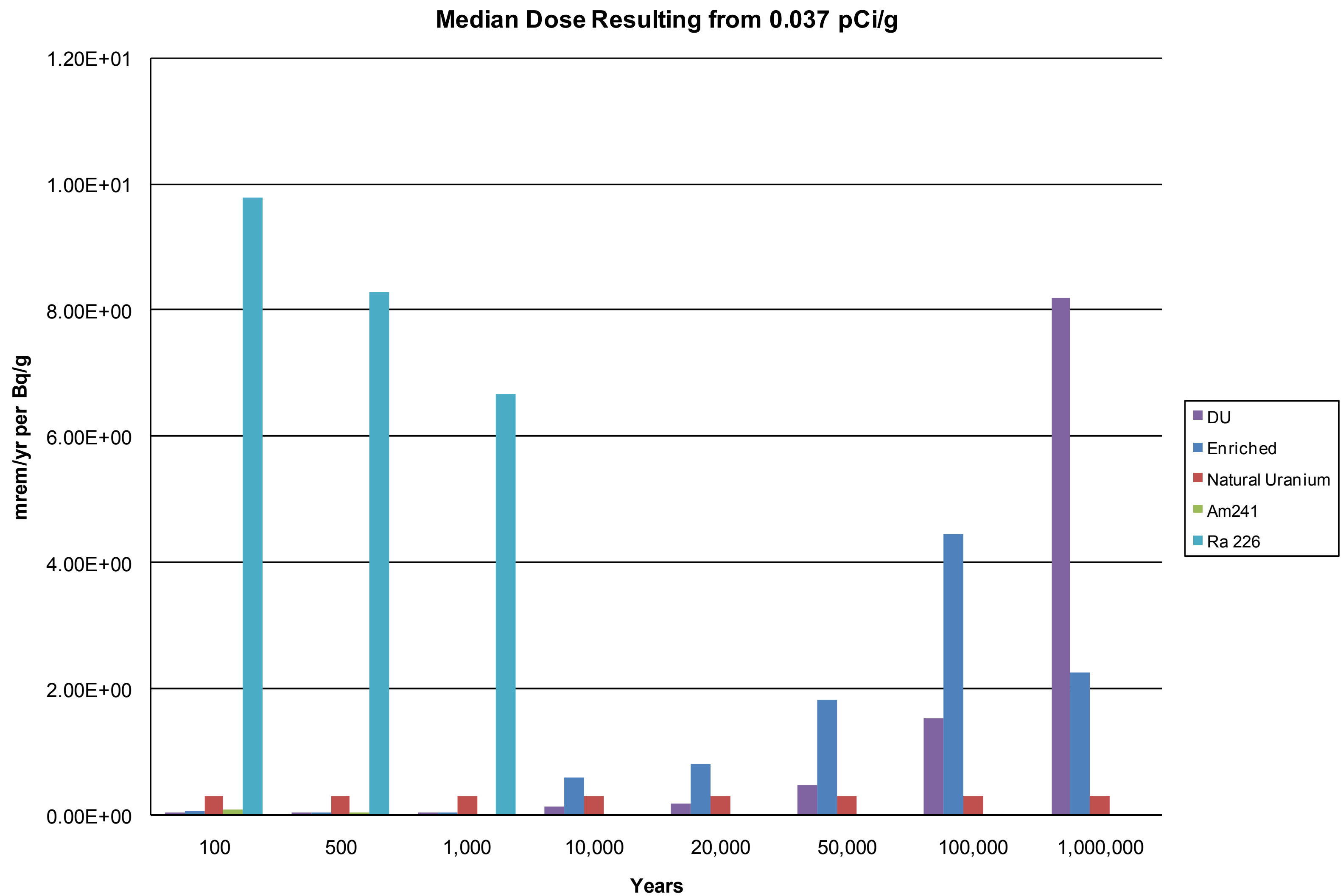

Figure 2b **Median Dose at Time t resulting from .037 Bq/g of Material Type at Year Zero**

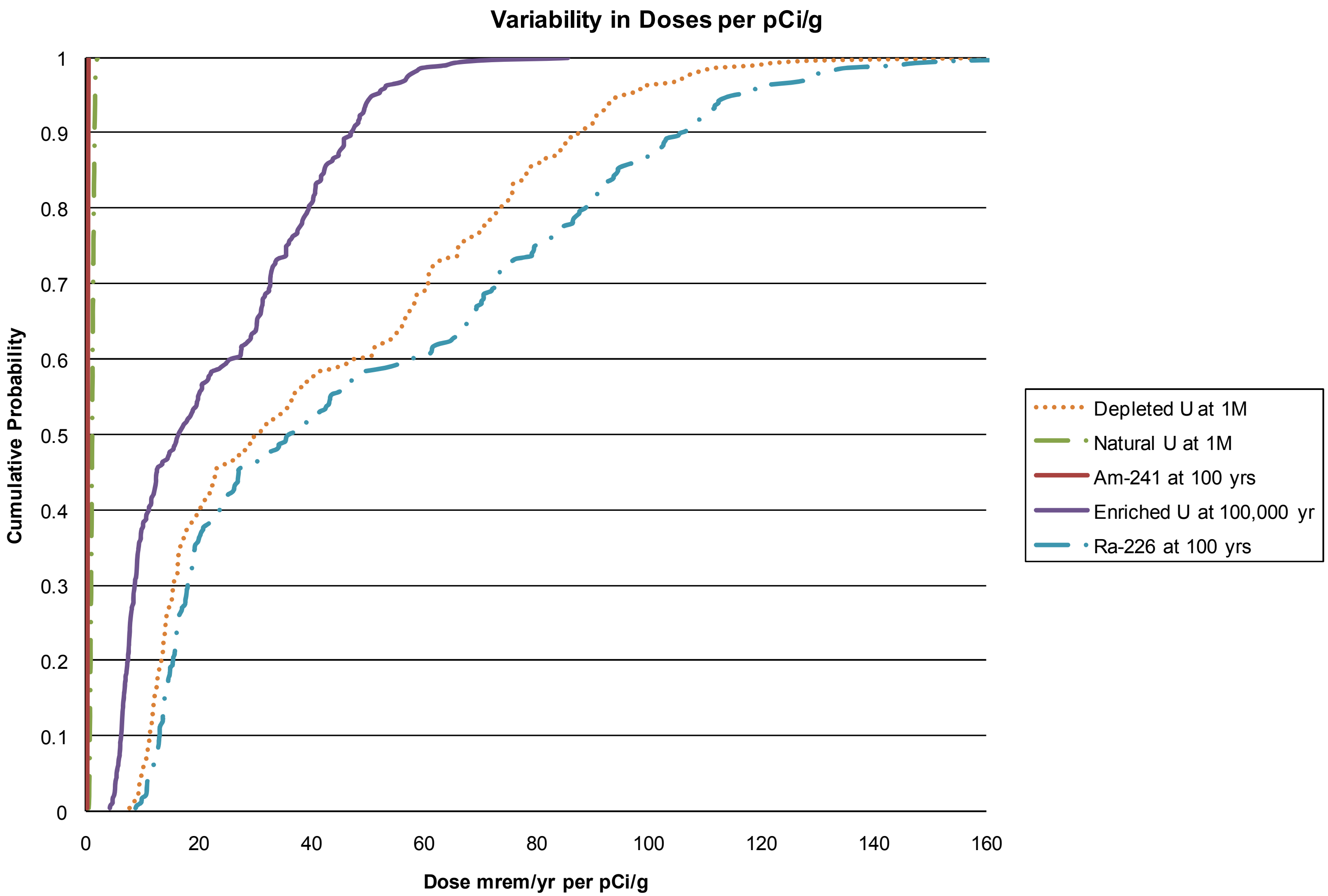

Figure 3a **Cumulative Distribution Function Showing Variability in Dose Results for Each Material Type**

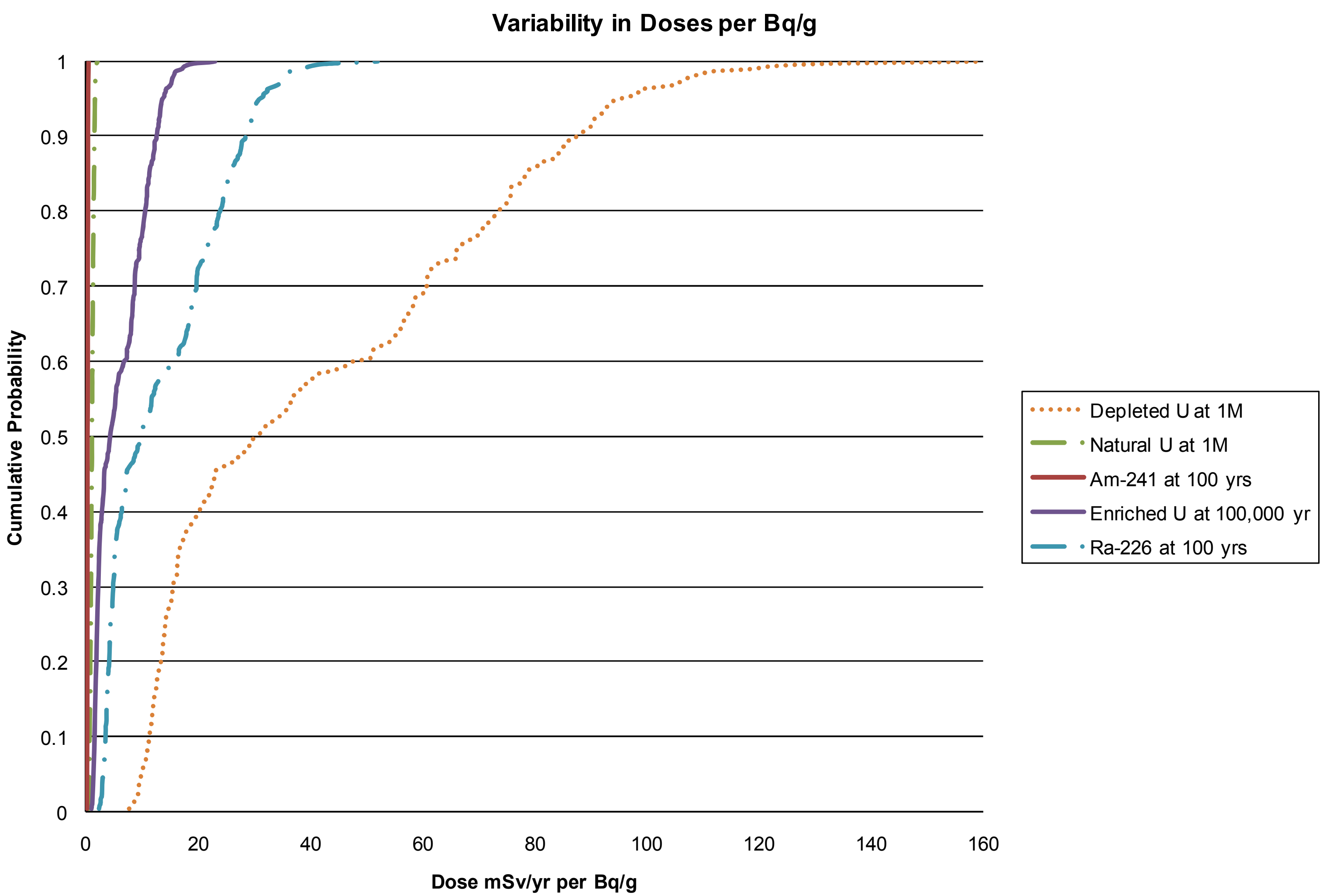

Figure 4b Cumulative Distribution Function Showing Variability in Dose Results for Each Material Type

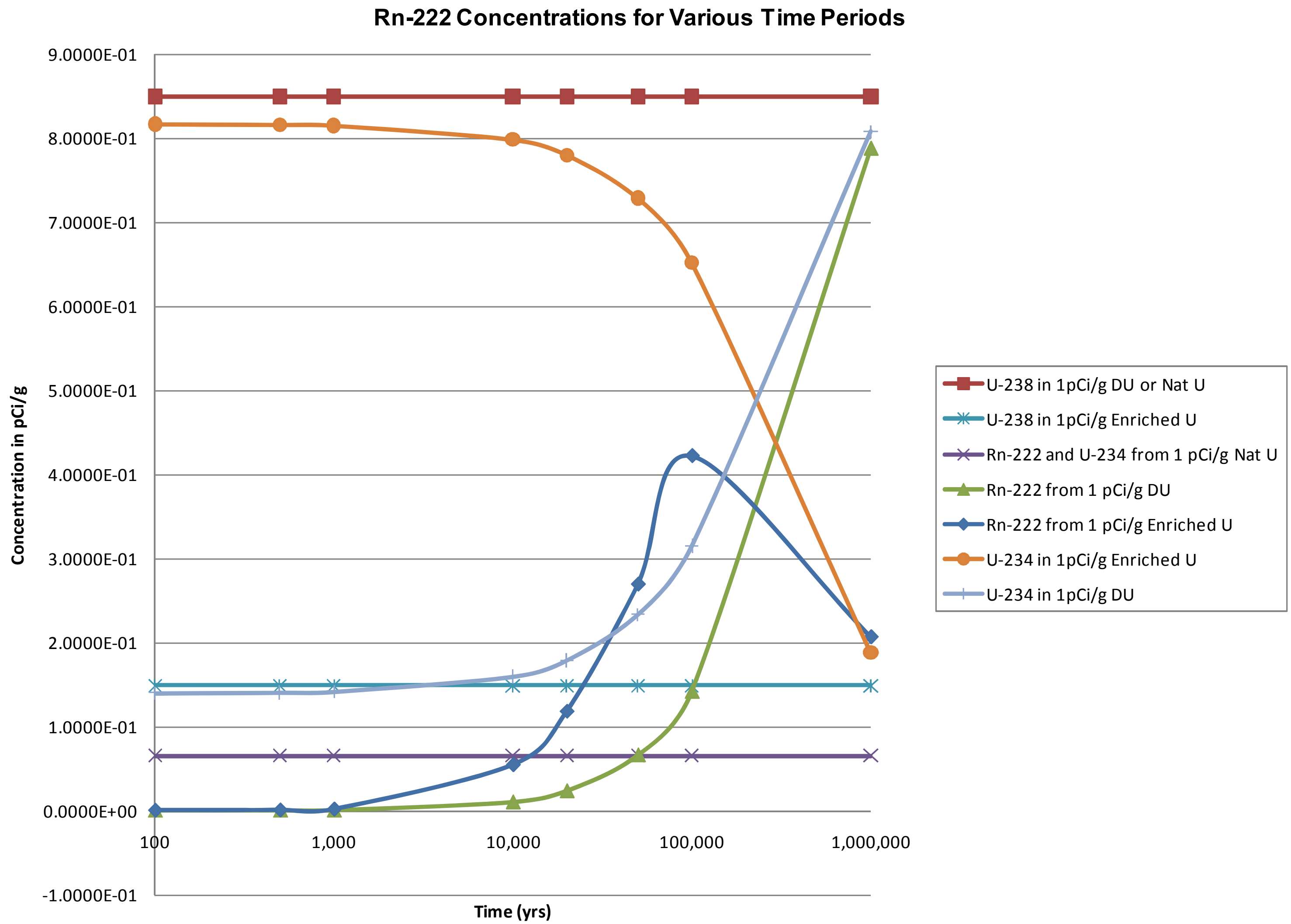

Figure 5 **In-growth of Rn-222 Concentration from 1 pCi/g Depleted or Natural Uranium**

Appendix A – Source Term Concentration Input Values

Natural Uranium	Concentration at Time Period (pCi/g)								
Radionuclide	0 yrs	100 yrs	500 yrs	1,000 yrs	10,000 yrs	20,000 yrs	50,000 yrs	100,000 yrs	1 Mill yrs
Ac-227	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Bi-211	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Fr-223	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Pa-231	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Pb-211	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Po-211	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Po-215	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Ra-223	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Rn-219	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Th-227	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Th-231	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Tl-207	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
U-235	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.692E-03	1.691E-03
Bi-210	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Bi-214	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Pa-234	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Pa-234m	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Pb-210	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Pb-214	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Po-210	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Po-214	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Po-218	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Ra-226	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Rn-222	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Th-230	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
Th-234	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
U-234	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02
U-238	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.520E-02	6.519E-02

Depleted Uranium	Concentration at Time Period (pCi/g)								
Radionuclide	0 yrs	100 yrs	500 yrs	1,000 yrs	10,000 yrs	20,000 yrs	50,000 yrs	100,000 yrs	1 Mill yrs
Ac-227		1.5968E-05	1.0663E-04	2.1925E-04	2.0553E-03	9.5042E-03	3.7246E-03	7.0536E-03	1.0798E-02
Bi-211		1.5942E-05	1.0660E-04	2.1922E-04	2.0553E-03	9.5042E-03	3.7246E-03	7.0536E-03	1.0798E-02
Fr-223		2.2036E-07	1.4715E-06	3.0256E-06	2.8363E-05	1.3116E-04	0.0000E+00	0.0000E+00	1.4902E-04
Pa-231		2.2844E-05	1.1374E-04	2.2628E-04	2.0612E-03	9.5050E-03	3.7289E-03	7.0557E-03	1.0798E-02
Pb-211		1.5942E-05	1.0660E-04	2.1922E-04	2.0553E-03	9.5042E-03	3.7289E-03	7.0557E-03	1.0798E-02
Po-211		4.3523E-08	2.9102E-07	5.9847E-07	5.6110E-06	2.5947E-05	0.0000E+00	0.0000E+00	2.9479E-05
Po-215		1.5942E-05	1.0660E-04	2.1922E-04	2.0553E-03	9.5042E-03	3.7289E-03	7.0557E-03	1.0798E-02
Ra-223		1.5942E-05	1.0660E-04	2.1922E-04	2.0553E-03	9.5042E-03	3.7289E-03	7.0557E-03	1.0798E-02
Rn-219		1.5942E-05	1.0660E-04	2.1922E-04	2.0553E-03	9.5042E-03	3.7289E-03	7.0557E-03	1.0798E-02
Th-227		1.5732E-05	1.0514E-04	2.1620E-04	2.0269E-03	9.3729E-03	3.7289E-03	7.0557E-03	1.0649E-02
Th-231		1.0808E-02	1.0808E-02	1.0808E-02	1.0808E-02	1.0807E-02	1.0808E-02	1.0808E-02	1.0798E-02
Tl-207		1.5899E-05	1.0631E-04	2.1862E-04	2.0497E-03	9.4782E-03	3.7289E-03	7.0557E-03	1.0769E-02
U-235	1.0808E-02	1.0808E-02	1.0808E-02	1.0808E-02	1.0808E-02	1.0807E-02	1.0808E-02	1.0808E-02	1.0798E-02
Bi-210		1.4907E-06	5.6021E-05	2.2334E-04	9.8695E-03	1.4135E-01	2.3169E-02	6.5841E-02	7.8793E-01
Bi-214		2.6829E-06	6.3448E-05	2.3726E-04	9.9130E-03	1.4143E-01	2.3222E-02	6.5881E-02	7.8810E-01
Pa-234		1.3593E-03	1.3593E-03	1.3593E-03	1.3593E-03	1.3593E-03	4.0099E-03	2.2343E-02	1.3591E-03
Pa-234m		8.4956E-01	8.4956E-01	8.4956E-01	8.4956E-01	8.4954E-01	8.4956E-01	8.4956E-01	8.4942E-01
Pb-210		1.4914E-06	5.6026E-05	2.2335E-04	9.8695E-03	1.4135E-01	2.3169E-02	6.5841E-02	7.8793E-01
Pb-214		2.6829E-06	6.3448E-05	2.3726E-04	9.9130E-03	1.4143E-01	2.3222E-02	6.5881E-02	7.8810E-01
Po-210		1.4706E-06	5.5896E-05	2.2310E-04	9.8687E-03	1.4135E-01	2.3169E-02	6.5841E-02	7.8793E-01
Po-214		2.6823E-06	6.3436E-05	2.3720E-04	9.9109E-03	1.4140E-01	2.3222E-02	6.5881E-02	7.8794E-01
Po-218		2.6835E-06	6.3461E-05	2.3730E-04	9.9149E-03	1.4146E-01	2.3222E-02	6.5881E-02	7.8826E-01
Ra-226		2.6843E-06	6.3465E-05	2.3730E-04	9.9149E-03	1.4146E-01	2.3222E-02	6.5881E-02	7.8826E-01
Rn-222		2.6835E-06	6.3461E-05	2.3730E-04	9.9149E-03	1.4146E-01	2.3222E-02	6.5881E-02	7.8826E-01
Th-230		1.2573E-04	6.2933E-04	1.2603E-03	1.2891E-02	1.4499E-01	2.6351E-02	6.9274E-02	7.8865E-01
Th-234		8.4956E-01	8.4956E-01	8.4956E-01	8.4956E-01	8.4954E-01	8.4956E-01	8.4956E-01	8.4942E-01
U-234	1.3963E-01	1.3983E-01	1.4064E-01	1.4164E-01	1.5948E-01	3.1488E-01	1.7877E-01	2.3348E-01	8.0779E-01
U-238	8.4956E-01	8.4956E-01	8.4956E-01	8.4956E-01	8.4956E-01	8.4954E-01	8.4956E-01	8.4956E-01	8.4942E-01

Enriched Uranium	Concentration at Time Period (pCi/g)								
Radionuclide	0 yrs	100 yrs	500 yrs	1,000 yrs	10,000 yrs	20,000 yrs	50,000 yrs	100,000 yrs	1 Mill yrs
Ac-227		5.1709E-05	3.4529E-04	7.0998E-04	6.6556E-03	1.2061E-02	2.2841E-02	3.0777E-02	3.4967E-02
Bi-211		5.1625E-05	3.4519E-04	7.0987E-04	6.6556E-03	1.2061E-02	2.2841E-02	3.0777E-02	3.4967E-02
Fr-223		7.1358E-07	4.7649E-06	9.7976E-06	9.1847E-05	0.0000E+00	0.0000E+00	4.2473E-04	4.8255E-04
Pa-231		7.3973E-05	3.6831E-04	7.3276E-04	6.6745E-03	1.2075E-02	2.2848E-02	3.0779E-02	3.4967E-02
Pb-211		5.1625E-05	3.4519E-04	7.0987E-04	6.6556E-03	1.2075E-02	2.2848E-02	3.0777E-02	3.4967E-02
Po-211		1.4094E-07	9.4238E-07	1.9380E-06	1.8170E-05	0.0000E+00	0.0000E+00	8.4021E-05	9.5459E-05
Po-215		5.1625E-05	3.4520E-04	7.0987E-04	6.6556E-03	1.2075E-02	2.2848E-02	3.0777E-02	3.4967E-02
Ra-223		5.1625E-05	3.4520E-04	7.0987E-04	6.6556E-03	1.2075E-02	2.2848E-02	3.0777E-02	3.4967E-02
Rn-219		5.1625E-05	3.4520E-04	7.0987E-04	6.6556E-03	1.2075E-02	2.2848E-02	3.0777E-02	3.4967E-02
Th-227		5.0943E-05	3.4047E-04	7.0011E-04	6.5636E-03	1.2075E-02	2.2848E-02	3.0352E-02	3.4485E-02
Th-231		3.5000E-02	3.5000E-02	3.5000E-02	3.5000E-02	3.5000E-02	3.5000E-02	3.4997E-02	3.4966E-02
Tl-207		5.1485E-05	3.4425E-04	7.0795E-04	6.6374E-03	1.2075E-02	2.2848E-02	3.0693E-02	3.4872E-02
U-235	3.5000E-02	3.5000E-02	3.5000E-02	3.5000E-02	3.5000E-02	3.5000E-02	3.5000E-02	3.4997E-02	3.4966E-02
Bi-210		8.7185E-06	3.2691E-04	1.2995E-03	5.3951E-02	1.1739E-01	2.6880E-01	4.2133E-01	2.0616E-01
Bi-214		1.5689E-05	3.7020E-04	1.3803E-03	5.4176E-02	1.1764E-01	2.6888E-01	4.2149E-01	2.0619E-01
Pa-234		2.3797E-04	2.3797E-04	2.3797E-04	2.3797E-04	7.0200E-04	3.9116E-03	2.3797E-04	2.3794E-04
Pa-234m		1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4870E-01
Pb-210		8.7226E-06	3.2695E-04	1.2996E-03	5.3951E-02	1.1739E-01	2.6880E-01	4.2133E-01	2.0616E-01
Pb-214		1.5689E-05	3.7020E-04	1.3803E-03	5.4176E-02	1.1764E-01	2.6888E-01	4.2149E-01	2.0619E-01
Po-210		8.6008E-06	3.2619E-04	1.2981E-03	5.3947E-02	1.1739E-01	2.6880E-01	4.2133E-01	2.0616E-01
Po-214		1.5686E-05	3.7012E-04	1.3799E-03	5.4164E-02	1.1764E-01	2.6888E-01	4.2140E-01	2.0615E-01
Po-218		1.5693E-05	3.7027E-04	1.3805E-03	5.4187E-02	1.1764E-01	2.6888E-01	4.2157E-01	2.0623E-01
Ra-226		1.5698E-05	3.7030E-04	1.3805E-03	5.4187E-02	1.1764E-01	2.6888E-01	4.2157E-01	2.0623E-01
Rn-222		1.5693E-05	3.7027E-04	1.3805E-03	5.4187E-02	1.1764E-01	2.6888E-01	4.2157E-01	2.0623E-01
Th-230		7.3506E-04	3.6670E-03	7.3132E-03	6.9514E-02	1.3142E-01	2.7851E-01	4.2643E-01	2.0586E-01
Th-234		1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4870E-01
U-234	8.1702E-01	8.1683E-01	8.1607E-01	8.1512E-01	7.9834E-01	7.8020E-01	7.2867E-01	6.5205E-01	1.8796E-01
U-238	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4873E-01	1.4870E-01

Am-241	Concentration at Time Period (pCi/g)				
Radionuclide	0 yrs	100 yrs	500 yrs	1,000 yrs	10,000 yrs
Ac-225		2.12E-23	2.27E-21	1.51E-20	2.74E-18
Am-241	1.00E-12	8.52E-13	4.48E-13	2.01E-13	1.08E-19
At-217		2.12E-23	2.27E-21	1.51E-20	2.74E-18
Bi-213		2.12E-23	2.27E-21	1.51E-20	2.74E-18
Fr-221		2.12E-23	2.27E-21	1.51E-20	2.74E-18
Np-237		2.99E-17	1.11E-16	1.61E-16	2.01E-16
Pa-233		2.99E-17	1.11E-16	1.61E-16	2.01E-16
Pb-209		2.12E-23	2.27E-21	1.51E-20	2.74E-18
Po-213		2.07E-23	2.22E-21	1.48E-20	2.68E-18
Ra-225		2.12E-23	2.27E-21	1.51E-20	2.74E-18
Th-229		2.12E-23	2.27E-21	1.51E-20	2.74E-18
Tl-209		4.57E-25	4.89E-23	3.27E-22	5.91E-20
U-233		6.67E-21	1.37E-19	4.40E-19	8.07E-18

Ra-226	Concentration at Time Period (pCi/g)			
Radionuclide	0 yrs	100 yrs	500 yrs	1,000 yrs
Bi-210		9.26E-13	8.16E-13	6.57E-13
Bi-214		9.57E-13	8.05E-13	6.48E-13
Pb-210		9.26E-13	8.16E-13	6.57E-13
Pb-214		9.57E-13	8.05E-13	6.48E-13
Po-210		9.25E-13	8.16E-13	6.57E-13
Po-214		9.57E-13	8.05E-13	6.48E-13
Po-218		9.58E-13	8.05E-13	6.48E-13
Ra-226	1.00E-12	9.58E-13	8.05E-13	6.48E-13
Rn-222		9.58E-13	8.05E-13	6.48E-13