

Risk-informed Analytical Approaches to Concentration Averaging for the Purpose of Waste Classification - 9199

David W. Esh, Karen E. Pinkston, Cynthia S. Barr,
Anna H. Bradford, and A. Christianne Ridge,
U.S. Nuclear Regulatory Commission
11545 Rockville Pike, Rockville, MD 20852

ABSTRACT

Nuclear Regulatory Commission (NRC) staff has developed a concentration averaging approach and guidance for the review of Department of Energy (DOE) non-HLW determinations. Although the approach was focused on this specific application, concentration averaging is generally applicable to waste classification and thus has implications for waste management decisions as discussed in more detail in this paper. In the United States, radioactive waste has historically been classified into various categories for the purpose of ensuring that the disposal system selected is commensurate with the hazard of the waste such that public health and safety will be protected. However, the risk from the near-surface disposal of radioactive waste is not solely a function of waste concentration but is also a function of the volume (quantity) of waste and its accessibility. A risk-informed approach to waste classification for near-surface disposal of low-level waste would consider the specific characteristics of the waste, the quantity of material, and the disposal system features that limit accessibility to the waste. NRC staff has developed example analytical approaches to estimate waste concentration, and therefore waste classification, for waste disposed in facilities or with configurations that were not anticipated when the regulation for the disposal of commercial low-level waste (i.e. 10 CFR Part 61) was developed.

INTRODUCTION

In the United States, radioactive waste has historically been classified into various categories for the purpose of ensuring that the disposal system selected is commensurate with the hazard of the waste such that public health and safety will be protected. For example, low-level waste (LLW) is generally suitable for near-surface disposal whereas high-level waste (HLW) requires geologic disposal.

A number of factors, specific to commercial LLW disposal, were considered in the analysis for 10 CFR Part 61 to develop Class A, B, and C low-level waste classification limits provided in Tables 1 and 2 of 10 CFR 61.55. These concentration limits were developed considering a variety of scenarios (the limiting scenario was intruder construction) and current disposal practices at the time [1, 2]. The intruder construction scenario involved the excavation of a foundation of a house with direct exhumation of disposed waste. The scenario was appropriate for commercial low-level waste disposal which was envisioned to be in shallow trenches covering a large area (thousands of square meters). The concentration limits provided in Tables 1 and 2 were developed making certain assumptions regarding the exposure scenarios and radiological distribution of waste that a commercial LLW facility would likely receive, and the analysis used the most current information on internal dosimetry (i.e., ICRP-2) and disposal technology available in the 1980's [3]. Additional assumptions were included in the analysis, such as assumptions regarding the fraction of waste of a particular radiological composition that would likely be received at a commercial LLW disposal facility and the amount of dilution expected in the waste disruption scenario. For the set of assumptions, the concentration limits in Tables 1 and 2 and the disposal requirements ensure that an inadvertent intruder would not receive a dose exceeding an equivalent of 5 mSv [500 mrem] to the whole body.

The relationship between waste concentration and disposal depth was recognized in the Draft Environmental Impact Statement for 10 CFR Part 61 and updates to the impacts analysis [1, 2]. Although the concentration limits provided in Part 61 were based on an assumed excavation depth of 3 m, consideration was given to excavations that may be deeper than 5 meters such as for an industrial building. A subjective probability of 10 percent was assigned to the likelihood that a deeper excavation would be inadvertently constructed at a LLW facility resulting in disruption of the waste. Consideration was also given to robust intruder barriers and the impacts they may have on safety. Robust intruder barriers are required for the shallow commercial disposal of Class C waste. A robust intruder barrier was assumed to delay an intrusion event for up to 500 years. However, technological limitations and uncertainties of barrier performance were recognized such that even in the case of a "hot waste facility" (an engineered facility that would be constructed of high-strength reinforced concrete to contain high activity waste such as sealed sources), credit for the concrete as an intruder barrier for time periods exceeding one thousand years was not believed to be reasonable. For near-surface disposal there were considered to be technological limitations to preventing intrusion for very long periods of time.

The calculations to develop the Table 1 and Table 2 concentration limits in 10 CFR 61.55 to define Class A, B, and C waste were based on a number of important assumptions and considerations. Although a requirement is provided that Class C waste must either be commercially disposed of at depths greater than 5 m [16 ft] or have a robust intruder barrier that lasts for 500 years, the calculations assumed an excavation scenario for the intruder. The calculations also assumed that a large volume fraction of the waste at a commercial LLW facility would not be Class C waste. Therefore, credit for dilution or mixing of different concentrations of waste was provided. The calculations did not assume that all waste would be at the concentration limits. The current internal dosimetry at the time, Report 2 of the International Commission on Radiological Protection (ICRP-2), was used in deterministic analyses [3].

NRC staff evaluated the approach to waste classification for commercial LLW and developed guidance for determining waste classification for incidental waste. Incidental waste is waste resulting from the reprocessing of spent nuclear fuel that does not require disposal in a deep geologic repository in order to manage the risks that it poses. Incidental waste may include many different types of waste in a variety of disposal configurations. For example, incidental waste may include residual waste in piping that is near the land surface and does not have a robust intruder barrier. Residual waste in a tank that is much deeper than 5 m [16 ft] from the land surface and does have a robust intruder barrier may also be considered to be incidental waste. An alternative conceptual approach was developed for use in review of DOE waste determinations to allow for greater flexibility in accounting for unique disposal conditions. DOE uses site-specific analyses called "waste determinations" to help decide whether waste can be classified as incidental. The risk informed approach accounted for 1) depth of waste, 2) intruder barriers, 3) more recent internal dosimetry (e.g., ICRP 26/30), and 4) propagation of uncertainty into the concentration limits. In essence, the approach is not constrained by a single set of assumptions. Example averaging expressions were developed to provide benchmarks for the NRC staff to use to risk-inform waste classification reviews of DOE waste determinations [4]. This paper provides the background, development approach, and a discussion of the applicability of the concept to other regulatory programs.

TECHNICAL APPROACH

Conceptually, waste classification is a practical mechanism to sort a continuous distribution of waste types into manageable groups to ensure safety of the public and workers from disposal activities. Waste type is considered to include variability in the isotopes, concentration, and quantity of radionuclides present in the waste. The basic elements of a safety decision for waste disposal are expressed below in equation form:

$$Safety = \frac{1}{Waste Risk} * Disposal System Protection * Environmental System Protection \quad (Eq.1)$$

In order to mitigate higher waste risk (e.g. higher concentrations and quantities), more protection by the disposal and environmental systems is needed. The desired safety to be achieved is generally set by regulatory agencies. The disposal system and associated disposal requirements, along with the environmental system in which the waste is disposed of, limit accessibility to the waste. Waste classification systems ensure that the accessibility of the waste is selected commensurate with the risk posed by the waste such that the desired level of safety will be achieved.

The risk from the near-surface disposal of radioactive waste is not just a function of concentration, but also the volume of waste, its accessibility, and its dispersibility. The accessibility and dispersibility of the waste may be limited by the wasteform, disposal system, and disposal environment. An alternative conceptual approach to calculating the concentration of radionuclides to compare to the concentration limits in the waste classification tables in 10 CFR Part 61 was needed for DOE waste determinations. The approach used to develop Part 61 in the 1980's employed a single set of assumptions, which are applicable for the disposal of commercial low-level waste. However, these assumptions may be overly constraining for other applications.

Figure 1 provides a comparison of the key assumptions of the intruder excavation scenario for Part 61 and the intruder scenarios that may be applicable to residual waste in a tank used to store high-level waste. Part 61 applies to the disposal of waste in the near surface, which is defined to be the top 30 m of the environment from the land surface. All of the waste shown in Figure 1 is near surface disposal. Whereas the excavation scenario is applicable for relatively shallow waste, the excavation scenario is not appropriate for deeper waste that is significantly below the expected excavation depth but would still be considered to be near surface disposal. In these cases, a drilling scenario may be more appropriate.

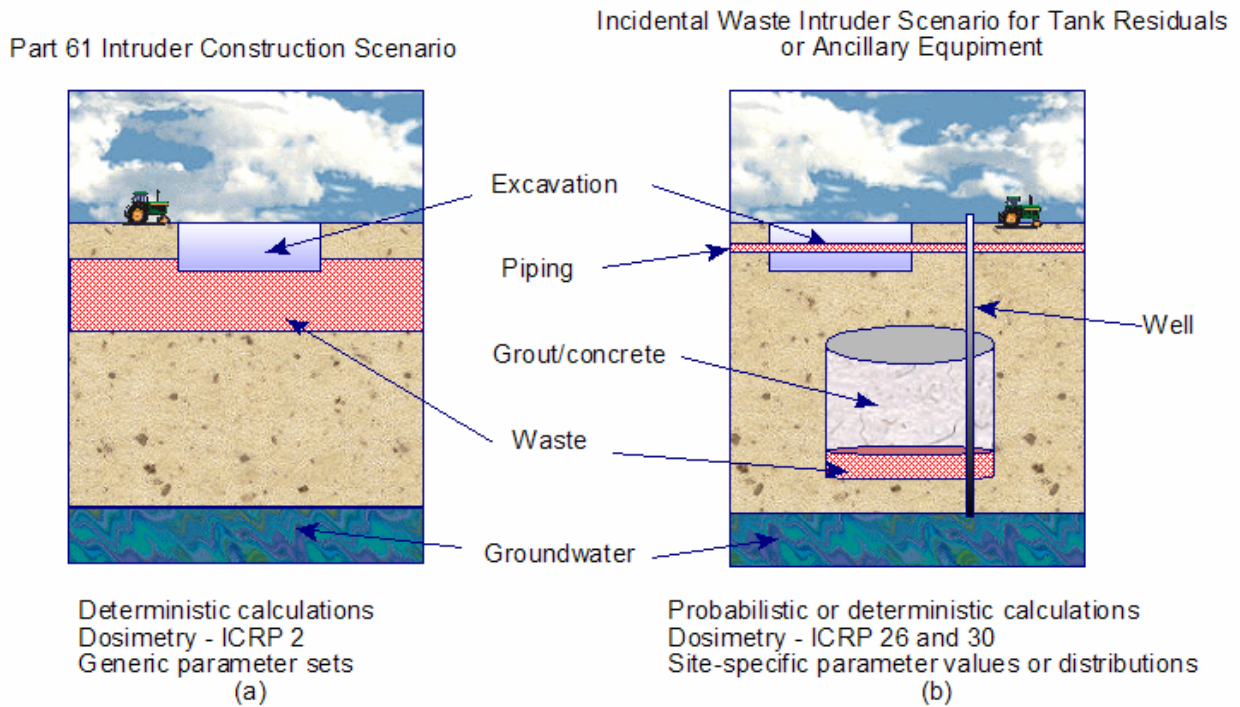


Fig. 1. Comparison of Key Assumptions of (a) the Intruder Excavation Scenario for Part 61 and (b) The Intruder Scenarios for Tank Residual Waste

Given the potential differences in key assumptions provided above, NRC staff needed a way to efficiently evaluate waste classification calculations performed for DOE waste determinations without replicating the full Part 61 analyses. The approach taken was to develop example concentration averaging expressions as a review tool. Example concentration averaging expressions were developed using a risk-informed approach to account for (1) depth of waste, (2) intruder barriers, (3) current dosimetry, and (4) propagation of uncertainty into the concentration limits. The example averaging expressions represent a conversion from the analyses used to support the development of Tables 1 and 2 of 10 CFR 61.55 [Figure 1(a)] to calculations more appropriate for incidental waste [Figure 1(b)]. Ideally this approach could be extended to other waste classification problems.

The Ronald W. Reagan National Defense Authorization Act for Fiscal Year 2005 (NDAA), applies different criteria dependent upon whether the incidental waste exceeds or does not exceed the concentration limits for Class C LLW. Therefore a classification determination is needed for incidental waste under the NDAA. Concentration averaging expressions would not be necessary if there was not a need to compare the concentrations of waste to the Table 1 and 2 values of 10 CFR 61.55 to determine its classification. The most direct approach would be to perform a site-specific intruder analysis that would define the quantities and concentrations of waste that could be safely disposed of at a particular site (i.e., site-specific waste classification). The disposal site would establish waste acceptance criteria which would be defined based on a site-specific analysis approved by the pertinent regulatory agency. Then a waste generator could show that their waste met the acceptance criteria for the disposal facility. From a risk perspective, this would be the most appropriate approach.

However, if a straightforward metric to determine waste classification is desired and it is to be applied at a national level, then an approach where the regulatory agency determines concentration limits for a reasonably conservative scenario that would be protective for a range of different disposal sites and

systems is more favorable. This is what was done for 10 CFR Part 61, at the expense of decreasing but not eliminating flexibility to risk inform disposal practices.

The other benefit of the approach used in the regulation is to decrease speculation and interpretation with respect to future human activity at a site. Different stakeholders have a broad range of opinions on the appropriateness of future land use scenarios. Selection of an appropriate land use scenario is challenging, because human behavior is very dynamic. Population density and land use was significantly different a few hundred years ago from what it is today and it is likely to be different a few hundred years in the future. In general, human activities that could result in disruption and exhumation of waste have tended towards more intrusion. For example, development of water resources has proceeded from direct use of surface water bodies to dug wells to shallow cased wells to deep drilled wells. The scarcity of resources will drive technologies to recover them. Industrial activity and development has resulted in deeper and larger excavation depths and population growth has resulted in more areas being disturbed over time. Development of environmental assessment and detection technology may mitigate the potential for increased disruption through the ability to detect and mitigate potential contamination. Increased flexibility to account for different waste concentration distributions, disposal technologies, and disposal sites can be added as long as a reasonably conservative scenario is selected for potential future human disruption/land use of the site.

Conceptually, the approach to develop the averaging expressions was based on the following equation:

$$C_{i,j} * V_i * X_{i,j} = D_{i,j} \quad (\text{Eq. 2})$$

where

- i = the analysis index (set to either 61 or N)
- j = the radionuclide index
- C_{i,j} = the concentration of radionuclide j for analysis i
- V_i = the volume of waste exhumed for analysis i
- X_{i,j} = a conversion factor for analysis i and radionuclide j to convert a source into an intruder dose (see Eq. 4 and explanation)
- D_{i,j} = the resultant dose to the intruder for analysis i from radionuclide j

The analysis index, i, is either the Part 61 waste classification analysis (61) or the new analysis for incidental waste (N). Equation (2) can be written for both the Part 61 waste classification analysis and the new analysis for incidental waste, and the two equations can be combined as Eq. (3)

$$\frac{C_{N,j}}{C_{61,j}} * \frac{V_N}{V_{61}} * \frac{X_{N,j}}{X_{61,j}} = \frac{D_{N,j}}{D_{61,j}} \quad (\text{Eq. 3})$$

The conversion factor X_{i,j} essentially represents the dose analysis to convert a quantity and distribution of radionuclide j into dose for analysis i. Many variables comprise the calculation of the conversion factor X_{i,j}, including but not limited to dosimetry, parameters, uncertainty treatment, and assumptions. The assumptions include but are not limited to assumptions with respect to the appropriate scenario and resultant mixing/dilution factors. The parameter X_{i,j} in equation 3 is a complex transfer function of these variables.

$$X_{i,j} \approx \text{Dosimetry}_{i,j} * \text{Parameters}_{i,j} * \text{Uncertainty}_{i,j} * \text{Assumptions}_{i,j} \quad (\text{Eq. 4})$$

Although the Part 61 analysis could be duplicated to define the variables influencing $X_{61,j}$, the effort required would be substantial. A simpler but valid approach was used to develop example averaging expressions for the staff to use as a review tool. If it can be assumed for the Part 61 analysis that the waste at the Class C limit for each radionuclide j multiplied by a conversion factor X_j resulted in a dose of 5 mSv [500 mrem] for the excavation intruder, then all of the variables except a new constant [$V_{61} * X_{61,j}$] are known in Eq. (2). Equation 3 was rewritten as

$$\frac{C_{61} * V_{61} * X_{61}}{D_{61}} = 1 = \frac{C_N * V_N * X_N}{D_N} \quad (\text{Eq. 5})$$

The next step is to substitute in known information and rearrange into a useful form. In this case NRC staff wanted to provide an equation that was a function of key scenario variables that would reflect the amount of mixing expected. Therefore, a portion of the equation can be rewritten as

$$V_i * X_i = f(SM_i, PAF_i) = b * SM_i * PAF_i \quad (\text{Eq. 6})$$

where

SM_i = ratio of the volume of waste exhumed to the total volume of material exhumed (m^3/m^3),
 PAF_i = dose per unit volume of waste for analysis i (complex function of the dose assessment) (rem/m^3)
 b = new constant (m^3).

Substituting Eq. 6 into Eq. 5 and rearranging yields

$$RC_i = \frac{D_N}{D_{61}} = \frac{C_N}{C_{61}} * SM_N \frac{PAF_N}{SM_{61} * PAF_{61}} = \frac{C_N}{C_{61}} * SM_N * Constant \quad (\text{Eq. 7})$$

where

RC_i = the radionuclide classification index for radionuclide i .

The radionuclide classification index represents the contribution of an individual radionuclide to the waste class, and overall classification is determined by a sum of fractions approach. Equation 7 has been written such that the relevant scenario mixing parameters (e.g., waste thickness and drilling depth for an intruder drilling scenario) could be reflected in the radionuclide classification calculation. The example below is one of the expressions developed for staff use as a review tool on incidental waste reviews. The example provides the expression for waste buried at depths greater than 5 m with a robust intruder barrier installed. The constant in Eqn. 8 is developed using the approach outlined in Eqns. 2 to 7, which required a performance assessment calculation to develop PAF_N that is part of the constant in Eqn. 7.

Example for waste buried at depths greater than 5 m with a robust intruder barrier

For Table 1 or Table 2 radionuclides, individual radionuclide contribution to the sum of fractions may be estimated with the following equation (drilling is assumed to occur at 500 years)

$$RC_i = \left(\frac{WC_i}{Table_value_i} \right) * \left(\frac{Waste_thickness}{Drill_depth} \right) * 7 \quad (\text{Eq. 8})$$

where

i	=	radionuclide index
RC_i	=	radionuclide classification factor (unitless)
WC_i	=	concentration in the waste for radionuclide i in units consistent with the appropriate Table value in 10 CFR 61.55
$Table_value_i$	=	Class C concentration limit in the appropriate Table of 10 CFR 61.55 for radionuclide i
$Waste_thickness$	=	thickness of the waste (m)
$Drill_depth$	=	depth an intruder would likely install a well in order to recover resources (m)

For incidental waste disposal, the expression was arranged for the primary variables of interest (e.g. waste volume or waste thickness and drilling depth) and different expressions were developed for different scenarios (e.g. waste access time, waste disruption type, receptor type). For a different application, a different expression could be developed based on the primary variables of interest for that application.

A radiological assessment was needed in order to develop the averaging expressions. The dose assessment provided the conversion factor $X_{N,j}$ for a given volume and concentration of waste. The radiological assessment method to develop the example averaging expressions calculated total effective dose equivalent (TEDE) as the product of radionuclides concentrations in environmental media and pathway dose conversion factors (PDCFs). The PDCFs were derived similarly to the method of Kennedy and Strenge (1992) for converting residual contamination into TEDE. The concentrations in environmental media were estimated by first calculating mixing of a user-defined source for a given intruder scenario (e.g., intruder drilling chronic, intruder construction acute), then applying simple mass transfer models to estimate radionuclide concentrations in air, water, and soil to account for radionuclide decay including ingrowth of daughters, sorption, solubility limits, hydrologic transport, and other mass transfer and partitioning processes. The pathways considered for the acute scenarios were inhalation, direct radiation, and inadvertent soil ingestion. In addition to the acute pathways, consumption of plants and animals were considered for the chronic pathways. Other pathways may need to be considered in the site-specific analysis (e.g., dependent on site conditions, the drinking water pathway may or may not be substantially delayed and the impacts might be smaller than the direct waste exposure pathways). To develop the benchmark expressions, the animal consumption pathway was not a dominant contributor for limiting short-lived (Cs-137) and long-lived (Np-237) radionuclides. In addition, the scenario was defined as a resident but not a resident-farmer, thereby making the animal pathway less credible. Therefore, the animal pathway was not implemented in the final calculations. For the excavation chronic scenario, the resident was assumed to grow food crops and was exposed through ingestion of the food crops. Plant/soil concentration ratios were used to estimate the amount of radioactivity taken into the plant from a unit activity in the soil. Four different plant parts were estimated separately: leaf, root, fruit, and grain.

Parameter uncertainty was explicitly considered in many of the inputs. Data used in the analysis were consistent with previous assessments of Kennedy and Strenge (1992) and default inputs in regulatory products (e.g., RESRAD, D&D). The dynamic simulation software package GoldSim® was used to perform the analysis. Probabilistic analysis was used in the development of the example averaging expressions to account for variability and uncertainty (e.g., uncertainty in soil-to-plant transfer factors). A probabilistic assessment was preferred because the impact of uncertainty and variability was factored into the averaging expressions. Parameters that should have been represented stochastically were determined on a case-by-case basis.

The new dose concentration ratio was defined as the dose resulting from a unit input of each radionuclide in the probabilistic analysis. In the analysis used to develop the example averaging expressions, the new dose concentration ratio, regardless of radionuclide, was sensitive to drilling scenario related parameters such as drilling depth, waste thickness, garden area, and drill cuttings distribution area. The new dose concentration ratio for excavation scenarios, regardless of radionuclide, was sensitive to the excavation-related parameters such as waste volume in the excavation and excavation volume. Parameters that directly define the concentration of waste in the environment after disruption can confidently be assumed to be important. For this analysis, the short-lived radionuclides were limited by Cs-137, and the long-lived radionuclides were limited by Np-237. The constant in the averaging expressions (see the example) were based on the limiting long- and short-lived radionuclides. Direct radiation exposure and plant consumption were the primary pathways for Cs-137, with inhalation and inadvertent soil ingestion secondary pathways. The doses from these pathways are sensitive to exposure times, consumption rates, soil-to-plant transfer factors, dose conversion factors, and transmission factors. For Np-237, the plant pathway and external radiation exposure were the primary pathways, with inhalation and inadvertent soil ingestion providing less than 10 percent of the total dose. Sensitive parameters were similar to those for Cs-137.

CONCLUSIONS

NRC staff has developed a concentration averaging approach to allow consideration of alternative scenarios, disposal depth, and intruder barriers for the review of waste classification in DOE non-HLW determinations. Although the approach was focused on this specific application, it may have more general applicability that could increase flexibility of waste management options while continuing to ensure protection of public health and safety. The approach considers that the risk from the near-surface disposal of radioactive waste is not solely a function of waste concentration but is also a function of the volume (quantity) of waste and its accessibility.

The low-level waste regulations and required analyses were based on an assumption of application commercial low-level waste practices common at the time of development of the regulation. In other words, the quantities of waste, the distribution of waste within a disposal system, and the type of disposal system were constrained. The risk to humans is directly related to the concentration of waste, how much waste is present, and how easy (or difficult) it is to disturb the waste and what scenarios could result in disruption of the waste. These variables dictate the potential concentrations of waste an inadvertent intruder could be exposed to. The developed concentration averaging approach provides a risk-informed method to assess waste classification within the existing regulatory framework.

REFERENCES

1. U.S. Nuclear Regulatory Commission (NRC), "Draft Environmental Impact Statement on 10 CFR Part 61, Licensing Requirements for Land Disposal of Radioactive Waste." NUREG-0782 (1981).
2. NRC, "Update of Part 61 Impacts Analysis Methodology." NUREG/CR-4370, Vol.1 (1986).
3. ICRP, "Report of ICRP Committee II on Permissible Dose for Internal Radiation." International Commission on Radiological Protection (1959).
4. NRC, "NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations." NUREG-1854 (2007).

5. NRC, "Residual Radioactive Contamination From Decommissioning." NUREG/CR-5512 (1992).