Using TableCalculator to Evaluate Parametric and Model Uncertainty in the Development of the NRC LLRW Classification Tables – 22180

Louis D. Caponi*, A. Christianne Ridge*, David W. Esh*, Patrick A. LaPlante**, and
Christepher A. McKenney*
*U.S. Nuclear Regulatory Commission
**Southwest Research Institute

ABSTRACT

In the United States, classification of low-level radioactive waste (LLRW) as Class A, B, C, or Greater-Than-Class C (GTCC) is based on radionuclide concentration limits provided in tables in Section 61.55 of Title 10 of the *Code of Federal Regulations* (CFR). In 2013, the US Nuclear Regulatory Commission (NRC) directed staff to consider a potential future rulemaking that could affect the waste classification tables based, in part, on the outcome of an ongoing, limited revision of 10 CFR Part 61. To prepare to complete that review and respond to potential stakeholder comments, the NRC staff developed tools to evaluate how changes to the original calculations based on updated knowledge would affect the results. The staff also prepared to compare the original calculations with the results of a modern probabilistic analysis.

During the development of 10 CFR Part 61 in the early 1980s, the NRC staff developed the LLRW classification tables based on model projections of dose to an inadvertent intruder in agricultural and construction scenarios at different times after closure of a hypothetical LLRW land disposal site. The staff performed the calculations with two deterministic Fortran codes, which are documented in NRC guidance documents published in the early 1980s. Although the equations and parameter values used in the codes are publicly available, no modern, user-friendly implementation of the codes had been developed by the NRC.

At the 2019 Waste Management Symposium, NRC staff presented the initial development of TableCalculator as a user-friendly tool to facilitate a more comprehensive understanding of the calculations used to develop the waste classification tables. The tool allows users to trace the original calculations and observe the effects of changes in parameter values by running the original calculations with the original or updated data. For example, users may update dose conversion factors from the original International Commission on Radiological Protection (ICRP) Publication 2 based dose conversion factors (DCFs) to values based on ICRP 26 and 30 or ICRP 72. The tool also provides users access to intermediate results, such as individual exposure pathway contributions, that were not provided as outputs from the original code.

The ability to update physical, physiologic, and behavioral parameters and to separate the effects of changing those parameters from scenario assumptions allows the user to identify significant assumptions that affected the basis for the original waste classification limits. In addition, the tool provides a centralized list of qualitative adjustments the NRC made during the original rulemaking process to account for waste accessibility, the probability of intrusion, and the expected composition of Class A and Class B waste, among other factors. That list, with accompanying references, makes it relatively easy for interested stakeholders to separate those qualitative adjustments from the concentration values that were "back calculated" based on a dose constraint.

The ability to change input parameters and evaluate intermediate model results allowed the NRC staff to identify differences between the original results and the results of a more modern intrusion analysis and to gain insights about the reasons underlying the differences. For example, the NRC staff observed large differences between the result of a modern analysis and the original results that could be explained because of changes to bone dosimetry between ICRP 2 and ICRP 26 and 30. Similarly, large differences between the original results and modern calculations for some radionuclides could be explained by

differences in the conceptual model for root uptake of radionuclides by plants. For some radionuclides, the difference between the results of the original analysis and a modern intruder assessment are dominated by adjustments the NRC made to the table values during the rulemaking process, as documented in public NRC documents from the early 1980s and referenced in the TableCalculator tool.

This paper demonstrates the use of a modern probabilistic assessment and deterministic TableCalculator analyses to evaluate assumptions in the original technical basis of the LLRW waste classification tables. This work also compares the magnitude of the effects of parametric changes to magnitude of effects of certain conceptual decisions made during the development of waste classification tables. The focus of the paper is on process and general considerations, rather than specific concentration limits for individual radionuclides. Should the Commission direct the staff to revise the tables, the NRC staff would develop specific results during the rulemaking process.

The NRC plans to make TableCalculator publicly available without cost on the Radiation Protection Computer Code Analysis and Maintenance Program (RAMP) website at https://ramp.nrc-gateway.gov.

INTRODUCTION

Purpose

This work demonstrates processes the NRC staff could use to develop risk insights for potential future consideration of revision to the waste classification limits, as directed by the Commission in a March 2013 Staff Requirements Memorandum [1]. Specifically, the authors used the TableCalculator tool, which allows modifications to the original calculations the staff used to develop the 10 CFR Part 61 waste classification tables, and a modern probabilistic intrusion analysis to evaluate the effects of parametric and conceptual model uncertainty on the limits provided in the waste classification tables. The focus of the current work is on demonstrating how the staff could use the combination of sensitivity analyses performed with the original deterministic calculations and a more modern probabilistic analysis to develop risk insights. Results presented in this work are intended to show the relative direction and magnitude of effects resulting from changing certain assumptions and parameters underlying the tables. The list of changes explored in this work is not exhaustive because the staff is in the preliminary stages of the activity.

Background

During the development of 10 CFR Part 61, the NRC staff developed two Fortran codes, called DOSE and INVERSI, to analyze various exposure scenarios to create the basis for the radionuclide concentration limits chosen to demarcate Class A, B, and C LLRW waste. The NRC developed those codes to perform a general technical analysis in the context of regulation development. The codes were not intended for site-specific analysis. The TableCalculator tool [2] replicates those codes and allows modifications to the calculations that were used to support the development of the 10 CFR 61.55 tables for classifying LLRW as Class A, B, C, or GTCC in the early 1980s [3,4]. The staff verified correct implementation of the code by comparing pathway dose conversion factors (PDCFs) calculated by the code to the PDCFs in the Draft Environmental Impact Statement (EIS) and Final EIS and by comparing final concentration results in the base case outputs for all 20 scenarios with results provided in NUREG-0959, Appendix 2 [5]. Additional details of the development and verification of TableCalculator were documented previously [2].

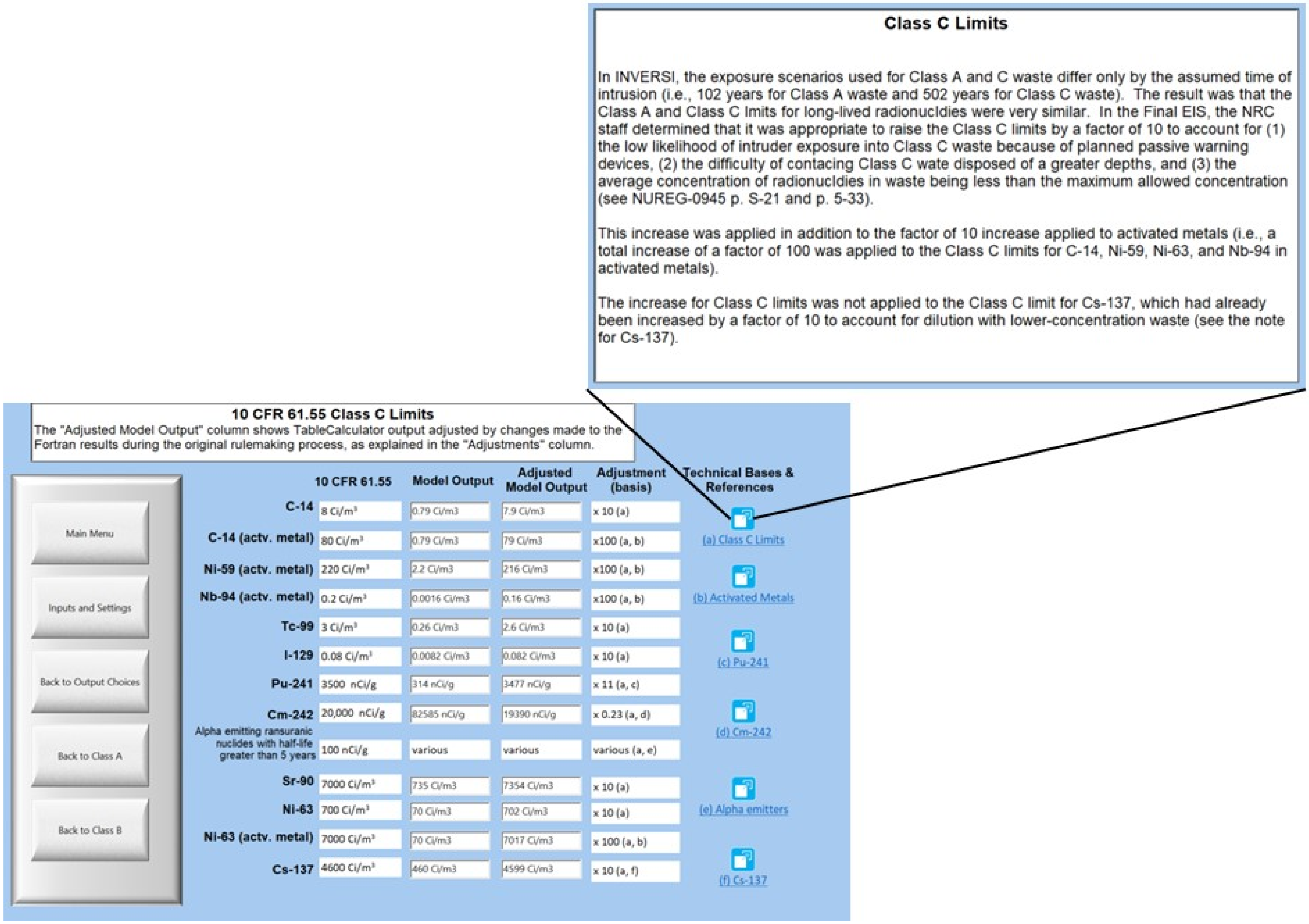
Although the NRC modeled and considered 20 exposure scenarios during the development of 10 CFR Part 61, the staff used five scenarios in the development of the waste classification tables. For Class A waste, the staff considered excavation of a residence and the resultant dose to a construction worker and an individual living onsite (i.e., excavation-construction and excavation-agriculture). The staff assumed intrusion into Class A waste could take place at 102 years after site closure, to account for 100 years of institutional controls and 2 years of closure activities. For Class B waste, the staff considered a shorter "discovery" exposure time during construction, based on the assumption that an individual would recognize stabilized Class B waste as a hazard and cease construction after 6 hours (i.e., excavation-discovery). For Class C waste, the staff considered the same two scenarios that the staff considered for Class A waste, except that staff increased the decay time to 502 years to account for the proposed requirement for either deeper disposal of waste or a 500-year intrusion barrier. For each scenario, the DOSE code generates PDCFs based on fundamental DCFs, transfer factors that account for radionuclide movement through environmental media, and uptake factors.

The staff developed the TableCalculator tool, in part, to improve the transparency of the original assumptions and calculations of the Fortran codes. The tool improves transparency by incorporating descriptions of parameter values and assumptions (i.e., text) and applicable references (i.e., links) to the original documentation in the tool interface. It also provides visualization of the flow of information (e.g., inputs, intermediate calculated results) through each step of the calculation. Users can evaluate the risk-significance of assumptions and parameter values by varying code input values. The tool includes outputs for derived radionuclide concentrations in waste, major contributing exposure pathways, and limiting organs (when applying ICRP 2). Figure 1 shows an example of an output screen that compares the tool output with values in the waste classification tables. More detailed output is available to show results for the other scenarios and radionuclides that were included in the original calculations but were not directly incorporated into the waste classification tables.

When executed with the default settings, the tool output matches the results of the original calculations. As described in the Draft EIS and Final EIS for the development of 10 CFR Part 61, the NRC made certain adjustments to the calculated concentrations to determine the concentration limits in the waste classification tables. Those adjustments included increasing the calculated concentrations to account for waste accessibility, radionuclide release, and the expected dilution of certain radionuclides in waste. To enhance transparency, the interface includes text to explain each adjustment, with references to the original documentation, accessible directly from the results screens. For example, Figure 1 shows a screenshot of the tool's comparison to Class C limits for the original tool configuration and parameter values. All changes to the original values (see, e.g., Table 7-1 of the Draft EIS [3]) are apparent between the "Model Output" and "Adjusted Model Output" columns. The tool provides the basis for each adjustment in notes on the right-hand side, which the user can click to expand for the full explanation of the adjustment.

During the development of TableCalculator, the NRC staff noted a small number of discrepancies between the original documentation and the Fortran code or within the code itself. Most of these discrepancies did not affect the waste classification tables. For example, as implemented in the INVERSI code, the calculation of doses from air pathways in the exposure scenario for construction at site with layered, stabilized waste in the construction scenario appears to include an extra factor of 0.1 beyond the shielding and time-reduction factors explained in the documentation. However, that factor does not impact the waste classification tables because the exposure scenario for construction worker exposure to stabilized, layered waste was not one of the five exposure scenarios used to develop the classification tables [2].

In contrast, one discrepancy in the code did affect waste classification tables. In the calculation of plant-based pathways, the original Fortran code added human plant ingestion values expressed on an annual basis to meat and milk ingestion expressed on a daily basis and interpreted the result as annual radionuclide ingestion. TableCalculator provides an input to run the code in the original configuration (for verification) and to correct the error (referred to as the "Animal Product Correction" in the Results Section below).



10 CFR 61.55 Class C Limits

The "Adjusted Model Output" column shows TableCalculator output adjusted by changes made to the Fortran results during the original rulemaking process, as explained in the "Adjustments" column.

	10 CFR 61.55	Model Output	Adjusted Model Output	Adjustment (basis)	Technical Bases & References
C-14	8 Ci/m³	0.79 Ci/m3	7.9 Ci/m3	x 10 (a)	(a) Class C Limits
C-14 (actv. metal)	80 Ci/m³	0.79 Ci/m3	79 Ci/m3	x100 (a, b)	
Ni-59 (actv. metal)	220 Ci/m³	2.2 Ci/m3	216 Ci/m3	x100 (a, b)	(b) Activated Metals
Nb-94 (actv. metal)	0.2 Ci/m³	0.0016 Ci/m3	0.16 Ci/m3	x100 (a, b)	
Tc-99	3 Ci/m³	0.26 Ci/m3	2.6 Ci/m3	x 10 (a)	
I-129	0.08 Ci/m³	0.0082 Ci/m3	0.082 Ci/m3	x 10 (a)	(c) Pu-241
Pu-241	3500 nCi/g	314 nCi/g	3477 nCi/g	x 11 (a, c)	
Cm-242	20,000 nCi/g	82585 nCi/g	19390 nCi/g	x 0.23 (a, d)	(d) Cm-242
Alpha emitting ransuranic nuclides with half-life greater than 5 years	100 nCi/g	various	various	various (a, e)	
Sr-90	7000 Ci/m³	735 Ci/m3	7354 Ci/m3	x 10 (a)	
Ni-63	700 Ci/m³	70 Ci/m3	702 Ci/m3	x 10 (a)	(e) Alpha emitters
Ni-63 (actv. metal)	7000 Ci/m³	70 Ci/m3	7017 Ci/m3	x 100 (a, b)	
Cs-137	4600 Ci/m³	460 Ci/m3	4599 Ci/m3	x 10 (a, f)	(f) Cs-137

Class C Limits

In INVERSI, the exposure scenarios used for Class A and C waste differ only by the assumed time of intrusion (i.e., 102 years for Class A waste and 502 years for Class C waste). The result was that the Class A and Class C lmits for long-lived radionucldies were very similar. In the Final EIS, the NRC staff determined that it was appropriate to raise the Class C limits by a factor of 10 to account for (1) the low likelihood of intruder exposure into Class C waste because of planned passive warning devices, (2) the difficulty of contacing Class C wate disposed of a greater depths, and (3) the average concentration of radionucldies in waste being less than the maximum allowed concentration (see NUREG-0945 p. S-21 and p. 5-33).

This increase was applied in addition to the factor of 10 increase applied to activated metals (i.e., a total increase of a factor of 100 was applied to the Class C limits for C-14, Ni-59, Ni-63, and Nb-94 in activated metals).

The increase for Class C limits was not applied to the Class C limit for Cs-137, which had already been increased by a factor of 10 to account for dilution with lower-concentration waste (see the note for Cs-137).

Figure 1. Screenshot of TableCalculator output showing the adjustments the NRC made for the concentration limits for each radionuclide and an example of the expanded explanation for one of the adjustments.

Additionally, the staff identified a small number of conceptual model assumptions in the original analyses that could be revisited. For example, in the original INVERSI code the staff implemented root uptake of radionuclides by multiplying radionuclide concentrations in a modeled mixture of waste and soil by both empirical waste-to-leachate partitioning factors and soil-to-plant transfer factors. For the original calculation, the staff based the waste-to-leachate factors on measured radionuclide concentrations in the waste and leachate at Maxey Flats and West Valley. However, in this work, the staff found that applying both factors was inconsistent with current practice for wastes that may degrade to soil-like states before intrusion. Modeling radionuclide leaching as a separate step prior to root uptake for those waste also appears to be inconsistent with the basis for the plant uptake factors, which were ratios of radionuclide concentrations in plants and soil (i.e., not liquid leachate).

Because plant uptake factors obtained from scientific literature compilations reflect a complex series of factors that contribute to the transfer of radionuclides from soil to plants and underlying studies have varying bases for these factors [5], the staff found the use of the waste-to-leachate partitioning factors in addition to the plant uptake factors to lack a clear basis in this context. For example, the staff found no clear basis for considering a different uptake of radionuclides into plants from Class A waste relative to soil. Furthermore, applying the partitioning factor double counted the factor of ten increase the NRC originally applied to radionuclide concentrations in activated metals. TableCalculator provides an input to toggle leachate partitioning on and off, which allows users to assess the impacts of applying the root uptake factors directly to the modeled radionuclide concentrations in soil rather than assuming the radionuclides must partition to leachate first.

METHODS

Future NRC review of the waste classification tables directed by the Commission [1] will include the staff's technical analyses, programmatic considerations, and stakeholder input. In this work, the NRC staff demonstrates three types of analyses the staff expects use to develop risk insights and to evaluate stakeholder comments in a potential future review. First, the staff has used the TableCalculator tool to evaluate the effects of certain parametric and conceptual changes to the original calculations. Parameter and assumptions explored in this work include dosimetry, adjustment factors applied during rulemaking, correction of an error in the original animal products pathways, and assumptions about radionuclide uptake by plants. Second, the staff compared the results of the deterministic sensitivity analyses performed with TableCalculator to the results of a more modern probabilistic intrusion analysis. Finally, the staff used the probabilistic model to evaluate parameters and assumptions that contribute most to the uncertainty in the projected dose per unit concentration in several intrusion scenarios.

The staff considered results in terms of waste concentrations derived from projected doses to a potential inadvertent intruder for different exposure scenarios. That is, the staff calculated the projected dose for a unit concentration of each radionuclide (with short-lived progeny that would be in secular equilibrium at the time of intrusion) and divided the limiting dose criterion by the dose per unit concentration. In the original analysis, the NRC staff derived waste concentrations based on the ICRP-2 critical organ approach, with organ dose constraints of 5 mSv (500 mrem) for the total body or bone; 15 mSv (1,500 mrem) for the liver, kidney, lung, or gastrointestinal tract/lower large intestine; and 30 mSv (3,000 mrem) for the thyroid. In analyses based on more modern dosimetry (i.e., DCFs provided in Federal Guidance Report (FGR) 11 [7], FGR 12 [8], ICRP 72 [9], and FGR 15 [10]), the NRC staff derived concentration constraints based on a 5 mSv/yr (500 mrem/yr) total effective dose equivalent (TEDE), consistent with the proposed changes to 10 CFR 61.42 [11].

In addition to the parametric tests the staff conducted with TableCalculator, the staff also compared TableCalculator results with the results of a probabilistic model developed by contractor staff of the Southwest Research Institute, Center for Nuclear Waste Regulatory Analyses (CNWRA). The contractor staff developed a modern intruder dose assessment using the BDOSE[a] [12] model developed with the commercial software package GoldSim[b] [13]. The NRC staff then compared results from these two different approaches to understand the impacts of different modeling approaches. The NRC staff previously took a similar approach in the analysis of GTCC waste [14].

To develop the probabilistic model, the CNWRA staff used the BDOSE 3.0 pathway dose model, which was developed specifically to evaluate intruder scenarios consistent with Part 61 requirements. The model included projections for two types of intrusion events: excavation and drilling. The excavation event represented the exhumation of diluted waste material from the excavation of a basement foundation during new residential construction. The drilling event represented the exhumation of diluted waste material during the complete construction of a well followed by the spreading of exhumed material on the land surface. The CNWRA staff calculated intruder scenario doses for three types of exposure scenarios: agricultural, construction, and discovery, consistent conceptually with the three types of scenarios used to establish Part 61. In the agricultural scenario, a resident lives on the site after excavated waste has been spread on the land surface and raises crops, poultry, and eggs on site. The construction scenario accounts for the dose to a construction worker who excavates the waste and builds a house onsite. The discovery scenario projects the dose to a construction worker who recognizes the waste as a hazard and leaves the site after a short time.

The model projected doses based on unit concentrations (1 Ci/m3) of each radionuclide in an assumed underground LLRW source. The staff then derived waste concentration limits corresponding to the projected doses by dividing a 5 mSv (500 mrem) TEDE annual dose limit by the projected dose for a unit concentration. The model used DCFs from FGR 11 and 12.

Using two groups of modelers with limited influence on one another and different models allowed the staff to explore the full uncertainty space associated with the outcomes to support more diverse, robust and risk-informed decision-making. Initially, the two groups proceeded independently. Then, as results were being produced, the NRC staff and the contractor met to discuss models, input data, and other considerations to understand similarities and differences in the results. Finding differences between the contractors' results and the TableCalculator results highlighted areas where conceptual model assumptions cause a significant difference in model projections (e.g., [14, 15]).

Finally, the NRC staff used the probabilistic sensitivity analysis capabilities of GoldSim to evaluate the parameters and assumptions that had the greatest effect on the projected dose to an inadvertent intruder. Continuing work will include similar analyses for additional radionuclides and scenarios, additional work to identify dominant exposure pathways, refinement of probabilistic distributions, and additional sensitivity and uncertainty analyses.

RESULTS

To demonstrate the types of parametric and conceptual model uncertainties the NRC staff plans to consider in a review of the waste classification tables, this section presents example analyses for four cases: Class C I-129, Class C Ni-59, Class A Sr-90, and Class A Cs-137. The staff focused on those cases because the derived concentrations for those radionuclides in those waste classes were sensitive to a variety of parameters and conceptual assumptions. Consideration of additional radionuclides would highlight additional parametric and conceptual issues the staff could consider when reviewing the

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[a] BDOSE – Biosphere Dose Model developed by staff at the Southwest Research Institute.

[b] GoldSim is a commercial software package developed by GoldSim Technology Group of Issaquah, WA.

technical bases for the classification tables. This section shows the effects of three types of changes: (1) concentration limit adjustments made during the original rulemaking, (2) updates to parameter values, and (3) conceptual model changes.

Figures 2 through 5 show the relative effects of changes to several conceptual assumptions and parameter values on derived radionuclide concentrations. For each figure, the red X symbols show values calculated deterministically with the TableCalculator tool using different inputs. The black circles show the mean of results from a modern probabilistic intruder analysis, with vertical bars representing the range from the 10th to the 90th percentile values. Each figure shows the ratios of the concentration derived by changing only the selected parameter to the original calculation without any regulatory adjustment factors (i.e., a one-on analysis). All values account for 102 years of decay for comparison to Class A limits or 502 years of decay for Class C waste.

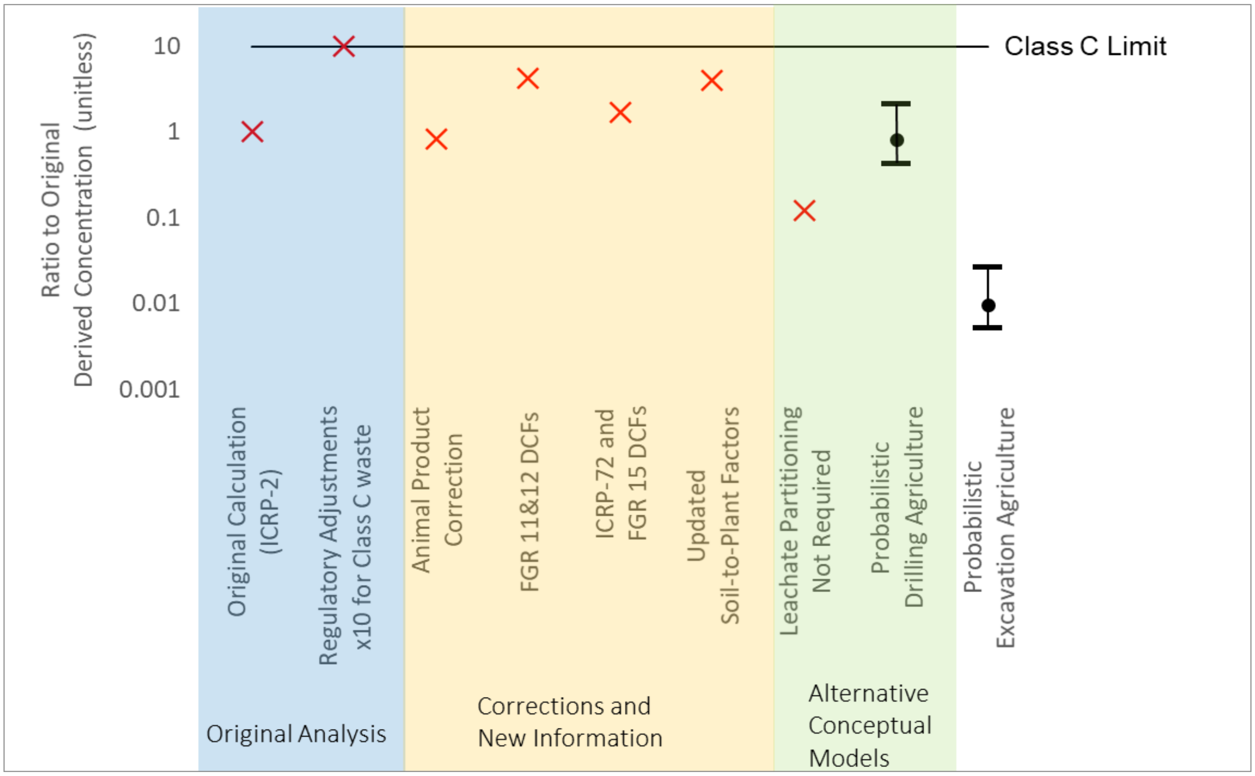

Figure 2. Effects of parameter and model changes on the derived concentration limit for Class C I-129 relative to the value calculated in the original rulemaking.

For example, for Class C I-129, the original result the NRC staff calculated during the development of 10 CFR Part 61 appears as the first red X on the left of Figure 2. That value matches the value shown in Table 7-1 of the Draft EIS. As described in the Final EIS, the NRC then applied a factor of ten increase to the calculated waste concentration to account for inaccessibility of Class C waste. The resulting concentration corresponds to the value in the waste classification tables and appears on the unity line in Figure 2.

As shown in Figure 2, changing from the original ICRP-2 DCFs to the DCFs in FGR 11 and 12 had a somewhat smaller effect on the derived I-129 concentration than the adjustment applied during rulemaking, increasing the derived concentration by approximately a factor of four. Further updating the DCFs to those given in ICRP-72 and FGR 15 had the opposite effect. Correcting for the unit conversion error in the animal product pathway had a relatively small effect.

One of the conceptual model uncertainties explored in the modern intrusion analysis was the exposure scenario. In the original analysis, the NRC assumed that Class C waste would not be intruded upon for 502 years after site closure because of the 10 CFR 61 requirement for either deeper disposal or a 500-year intrusion barrier. The staff assumed that, after that time, the waste could be excavated during construction of a residence. However, if disposal at depths greater than 10 m precluded excavation for a residence as a likely exposure scenario, a well drilling exposure scenario might be relevant.

In the current work, the staff considered both acute doses to the driller and chronic doses to an individual who lives in a residence and farms on land after drill cuttings are spread on the land surface and found that, in all cases, the chronic intrusion dose was limiting (i.e., resulted in a lower derived concentration than the acute drilling scenario). Because the radionuclide inventory exhumed in a drilling scenario is much smaller than the inventory exhumed during excavation of a foundation for a residence, the drilling scenario yielded lower dose projections and correspondingly greater derived concentrations. As shown in Figure 4 for I-129, the difference between the derived concentrations based on those two exposure scenarios (i.e., excavation and drilling) is similar to the range of effects of applying the factor of ten increase for Class C waste, updating the dosimetry, and changing the conceptual model for radionuclide uptake by plants.

The analysis for Ni-59 resulted in a much greater range of values than the results for I-129 (Figure 3). Part of that large range is explained by the additional factor of ten adjustment the NRC made to the Ni-59 to account for the slow release from activated metal. Another part of that large range is due to the significant change in DCFs for Ni-59 between ICRP-2 and FGR 11 and 12. As explained further below, the significant change in DCFs for Ni-59 is attributable to changes in the ICRP model of the bone between those two sets of DCFs. In addition, applying the change in the conceptual model for root uptake into plants had a larger effect for Ni-59 than it did for I-129.

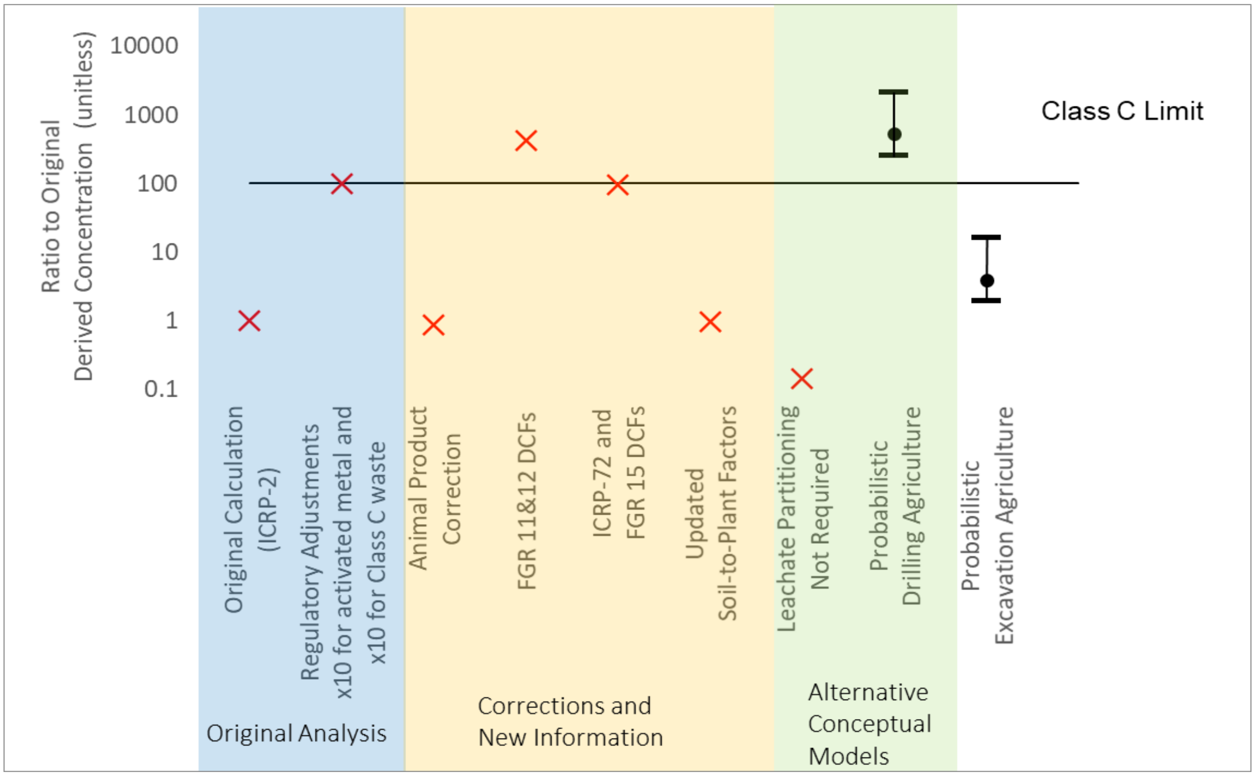

Figure 3. Effects of parameter and model changes on the derived concentration limit for Class C Ni-59 relative to the value calculated in the original rulemaking.

For Class A waste, the NRC staff expects excavation for a residence should be considered because Class A waste is typically disposed of closer to the land surface than Class C waste is. Therefore, the probabilistic model results shown in Figures 4 and 5 only show the concentrations derived from the 10th and 90th percentile doses projected from the excavation scenario in the modern probabilistic analysis and do not show results from a drilling scenario.

During the development of the waste classification tables, the NRC assumed that Class A waste containing Cs-137 was likely to be significantly diluted with Class A waste that contained no or very little Cs-137. As a result, the NRC increased the derived concentration for Class A Cs-137 from 1.6×10^9 Bq/m^3 [0.045 Ci/m^3] to 3.7×10^{10} Bq/m^3 [1 Ci/m^3] (i.e., a factor of 22 increase) [2]. That adjustment had a much greater effect on the derived concentration than any change in dosimetry or assumptions about root uptake of radionuclides in the original model (Figure 5).

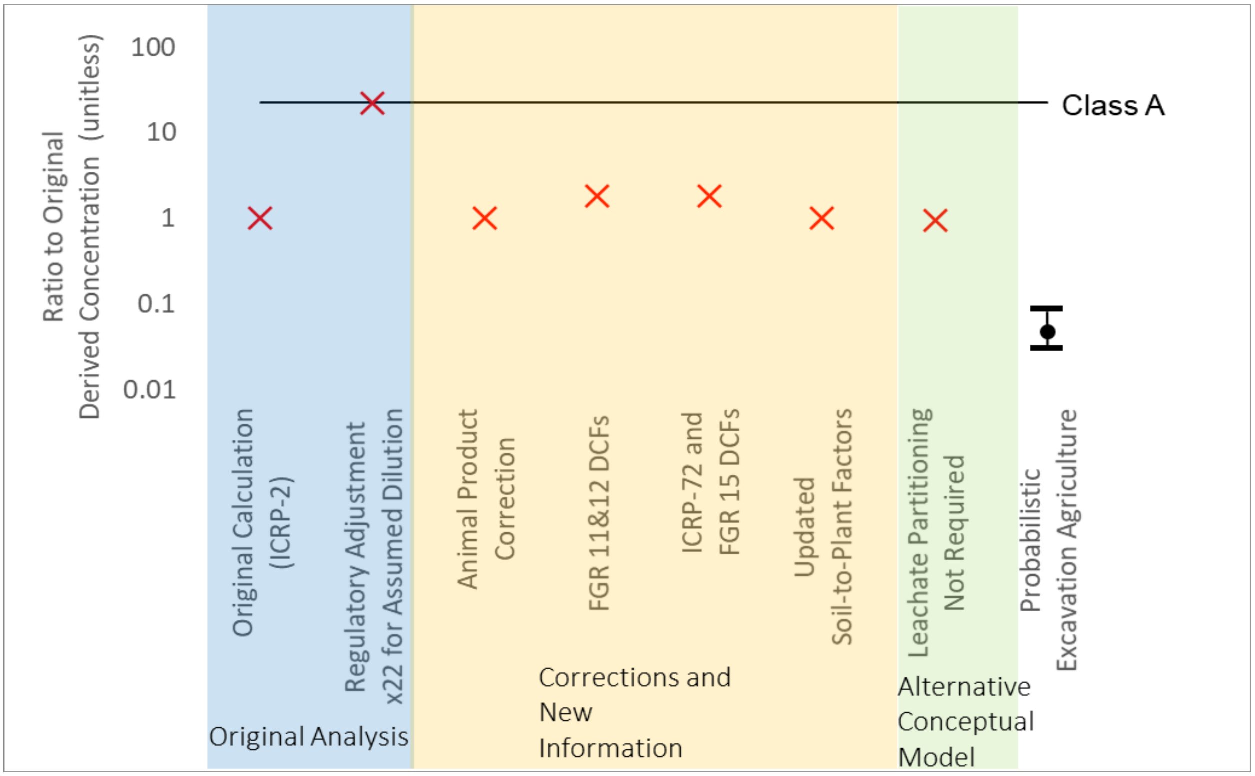

Figure 4. Effects of parameter and model changes on the derived concentration limit for Class A Cs-137 relative to the value calculated in the original rulemaking.

The final case the NRC staff considered in this work was the Class A limit for Sr-90 (Figure 5). In the original rulemaking, the NRC did not apply any adjustments to the Class A limit for Sr-90. Strontium-90, like Ni-59, is a bone-seeking radionuclide and shows a significant difference between the derived concentrations based on ICRP-2 dosimetry and concentrations based on FGR 11 and 12 DCFs. Because of the importance of the plant ingestion exposure pathway for Sr-90, updating the plant uptake model significantly decreased the derived concentration. The range of concentration values derived for Class A Sr-90 with the modern analysis overlaps the TableCalculator results run with updated DCFs after the leachate partition factor was removed (Figure 5). Removing the leachate partitioning factor is equivalent to assuming that plants can take radionuclides up from exhumed waste as easily as they take up radionuclides from soil. That is likely to be a poor assumption for wasteforms like activated metals but could be a good assumption for some forms of Class A waste.

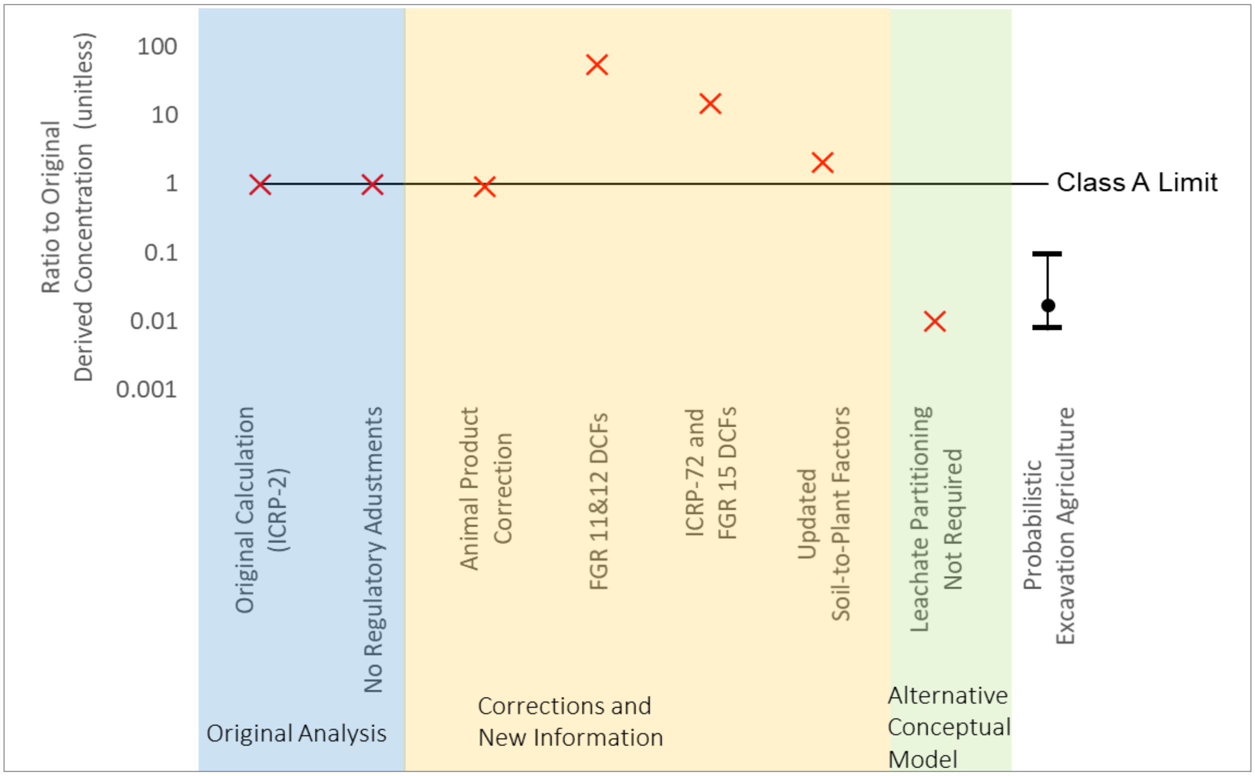

Figure 5. Effects of parameter and model changes on the derived concentration limit for Class A Sr-90 relative to the value calculated in the original rulemaking.

To better understand why the probabilistic model included a significant range of results below the derived concentrations based on variations of the original deterministic analysis for Class A Sr-90, the staff used sensitivity analysis features of the GoldSim modeling platform to determine which parameters had the greatest effect on the projected dose from Sr-90/Y-90. The three parameters with the greatest importance measures were the transfer factor for non-leafy vegetables, the annual consumption of non-leafy vegetables, and the annual consumption of leafy vegetables. The significance of those parameters is consistent with the importance of the plant ingestion in variations of the original analysis (Table I) as well as the dominant pathways identified in the modern analysis. The relationship between each of the three parameters with the greatest importance measures and the projected intruder dose from Sr-90/Y-90 in an excavation-agriculture scenario at 102 years after site closure is shown in Figure 6.

Table I shows the TableCalculator result for the major contributing dose pathways for an excavation-agriculture scenario at 502 years after disposal (i.e., the scenario the staff used to develop Class C limits in the original analysis), with the animal product pathway correction. Model runs using FRG 11 and 12 or ICRP 72 and 15 used direct exposure DCFs for a 15 cm depth of contaminated soil. Although the original Fortran codes calculated doses by summing exposure pathways, the intermediate pathway results were not available to the user in the original codes. The NRC staff added pathway outputs to TableCalculator to facilitate the development of risk insights when comparing variations of the original calculations to the results of a modern probabilistic assessment.

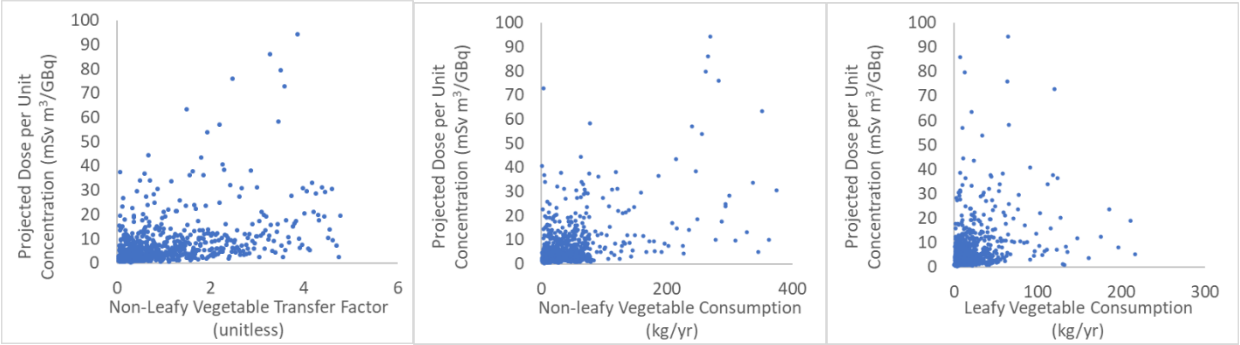

Figure. 6 Relationship between the projected dose from Sr-90/Y-90 per unit concentration for an intruder-excavation scenario 102 years after site closure and the three stochastic variables with the greatest importance measure

Table I: Major Contributing Pathway Analysis of Updated Dose Methodology for an Excavation-Agriculture Scenario at 502 Years After Site Closure

Radionuclide	ICRP 2		FGR 11 and 12		ICRP 72 and FGR 15	
	Leachate Partitioning Required	No Leachate Partitioning Required	Leachate Partitioning Required	No Leachate Partitioning Required	Leachate Partitioning Required	No Leachate Partitioning Required
Ni-59 in activated metal	Direct (soil volume)	Soil-plant-meat	Soil-plant-meat	Soil-plant-meat	Direct (soil volume)	Soil-plant-meat
Ni-63 in activated metal	Soil-plant-meat	Soil-plant-meat	Soil-plant-meat	Soil-plant-meat	Direct (soil volume)	Soil-plant-meat
Sr-90	Soil-plant	Soil-plant	Soil-plant	Soil-plant	Direct (soil volume)	Soil-plant
I-129	Direct (soil volume)	Soil-plant	Soil-plant	Soil-plant	Direct (soil volume)	Soil-plant
Cs-137	Direct (soil volume)	Direct (soil volume)	Direct (soil volume)	Direct (soil volume)	Direct (soil volume)	Direct (soil volume)

DISCUSSION

The NRC staff evaluated the relative importance of modeling choices made during the original development of the waste classification tables. In general, the original calculations and variations on those calculations were in agreement with the range of results from a modern probabilistic model. That is, the original derived concentrations and many of the variations on those results generally fell within the range of results generated by modern analyses (Figures 2, 3, and 5). One exception was the derived concentration for Class A Cs-137, for which the original analysis and all of the deterministic variations were greater than the upper end of the range of concentrations calculated with the modern assessment (Figure 4). The NRC staff is in the process of evaluating the assumptions underlying the probabilistic assessment to determine reasons for the difference between its results and the original, deterministic calculations.

The relative importance of modeling assumptions made during the original rulemaking depend on the waste class, wasteform, and radionuclide. For example, for Class C disposal of I-129 (Figure 2), the exposure scenario choice between drilling and excavation for a residence had a greater effect on the derived concentrations than any of the adjustments the NRC applied during the original rulemaking or updates to dosimetry or the plant uptake pathway. In contrast, for the Class C limit for Ni-59, choice of dosimetry, assumptions about Ni-59 release from activated metal, and assumptions about radionuclide uptake into plants all had significant impacts on the derived concentration that were as important as the conceptual choice of a drilling or excavation scenario for Class C waste.

The adjustments the NRC staff made to the derived concentrations during the rulemaking process may present a particularly good opportunity to apply knowledge and computational capabilities gained during the last 40 years. For example, the original rulemaking applied a simple factor of ten increase to the waste class limits for radionuclides in activated metal to account for the slow release of radionuclides from the waste. With the knowledge and computational advances that have taken place since the rule was developed, it might be possible to model the release from different waste types more specifically rather than applying a generic factor of ten. Similarly, knowledge gained during the last 4 decades could allow a reevaluation of the leachate partitioning factor in the original code to determine if it is generically applicable to all waste types, as was assumed in the original calculations.

Dosimetry is another area where significant advancements have been made since the NRC developed 10 CFR Part 61. For example, bone dosimetry models have been updated significantly since the publication of 10 CFR Part 61. As noted in FGR 11, ICRP 2 considered a marrow-free skeletal bone and averaged the dose across the entirety of the bone, only accounting for indirect effects of internal tissue. The bone model calculated dose based on a comparison of each radionuclide to Ra-226. A radionuclide-specific quality factor and relative damage factor were introduced to account for differences in radiological interactions as compared to Ra-226. The maximum permissible concentrations for bone-seeking radionuclides are reflective of this homogenous model and weighting factors. ICRP 26 and 30 apply an updated model that analyzes the dose to bone surfaces and active red bone marrow separately, while accounting for two types of bone structure: cortical (dense) and trabecular (spongey) bone. This methodology doubled the quality factor of alpha radiation. Six categories of radionuclides were created based on metabolic and dosimetric parameters, so the relative damage factor was removed from the calculations.

Stakeholders have previously suggested that the NRC could update the waste classification tables to reflect more modern dosimetry [16, 17]. As shown in Figures 2 through 5, updating the DCFs from values based on ICRP-2 to more modern values had a much greater effect on some radionuclides (e.g., Ni-59) than others (e.g., Cs-137). The results the staff found by updating DCFs in TableCalculator and leaving other parameters at their original values were generally consistent with the work of others [16,17]. However, the derived concentrations for (Ni-59, Ni-63, and Sr-90) increased more than they did in other analyses [16] when updating the DCFs.

To evaluate the reasons for the large increases, the NRC staff evaluated the limiting exposure pathways and critical organs in the original calculations. Staff noted that each of these radionuclides is bone-seeking and confirmed that the derived concentrations were limited by the dose to the bone in the original calculations based on ICRP 2. To make the original calculations more transparent, NRC staff added an output screen to TableCalculator to show the limiting organ for the derived concentration for each radionuclide when ICRP-2 dosimetry is used. Based on those critical organ outputs, the staff determined the change from the ICRP-2 bone dose to a TEDE based on more modern dosimetry was even greater than the change from an ICRP-2 "total body" dose to a modern TEDE. That larger difference explained the larger observed increase in the derived concentrations for bone-seeking radionuclides in this work as compared to previous analyses [16].

As previously noted, the parametric and conceptual variations evaluated in this work were provided to illustrate processes and tools the NRC staff would use in a potential review of the waste classification tables. The list of issues considered was not exhaustive because the staff is in the preliminary stages of work. For example, the NRC's "Technical Analysis of the Hazards of Disposal of Greater-Than-Class C (GTCC) and Transuranic Waste" [14] considered hazards attributable to both intrusion and accident scenarios. The original calculations performed during the development of the waste classification tables included both fire and container drop scenarios and TableCalculator includes those modules, although they were not used in this analysis.

CONCLUSION

This work illustrated some of the processes and tools the NRC staff could use in a potential review of the LLRW classification tables. The staff used variations on the original calculations and comparisons to a modern probabilistic assessment to find areas where updates to parameters or conceptual models may be appropriate during a potential review of the LLRW classification tables.

This work also illustrated the effects of changing certain conceptual assumptions and parameter values in comparison to the magnitude of adjustments the NRC staff made during the initial rulemaking process. Some of those adjustments, such as the assumed dilution of Cs-137 in Class A waste, were based on the best available knowledge and projections at the time the NRC developed the rule and could be verified or further adjusted with the benefit of 4 decades of additional information about waste characteristics. Other adjustments, such as the factor of ten increase in waste classification limits for certain radionuclides in activated metals, were not modeled explicitly at the time because of limited experimental evidence and computational power but could be incorporated into a modern intruder analysis.

The TableCalculator tool is well-suited to exploring the effects of updating parameters and conceptual models on derived concentrations of radionuclides corresponding to a dose criterion. It also serves as a knowledge management and communication tool by making the original calculations done during development of the tables more traceable and transparent.

Considering any one of the changes evaluated in this work in isolation could suggest specific changes to the classification limits; however, the variation discussed in this paper supports a more holistic view. To evaluate whether changes are warranted to the waste classification tables, the NRC staff would consider the types of parametric and conceptual model uncertainties addressed in this paper, in addition to risk insights gained from probabilistic sensitivity analyses as part of its decision-making process.

TOOL AVAILABILITY

The NRC plans to make TableCalculator publicly available, without cost, on the Radiation Protection Computer Code Analysis and Maintenance Program (RAMP) website at https://ramp.nrc-gateway.gov. The purpose of RAMP is to develop, maintain, improve, distribute, and provide training on NRC-sponsored radiation protection and dose assessment computer codes. To run the tool, an individual would need to download a free "player" program from the GoldSim Technology Group at https://www.goldsim.com/Web/Products/GoldSimPlayer/.

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