PERFORMANCE MODELING TO SUPPORT DECISION-MAKING FOR THE MANAGEMENT AND DISPOSITION OF LOW-ACTIVITY RADIOACTIVE WASTE

Kenneth S. Czyscinski, D.J.Scultheisz and R.T. Peake

U.S Environmental Protection Agency, Washington, D.C., USA

ABSTRACT

The Agency has been examining the potential for the use of the RCRA-C disposal unit technology for the disposal of "low-activity" radioactive wastes (considered as a subset of Class A wastes as defined by the NRC). To determine waste acceptance criteria (permissible radionuclide concentrations in the wastes), preliminary performance modeling of the RCRA-C disposal unit was conducted for an expected case (slow degradation of the disposal unit), as well as exposures through three human intrusion scenarios and worker exposures during waste handling, treatment, storage and transportation. The expected case modeling examined disposal units in arid and humid climates and in a variety of hydrologic settings. A set of linked codes were used to assess stochastic performance within the waste unit, along the ground water travel path and the biosphere to calculate doses to a near-by off-site receptor. Results showed that arid site locations offered exceptional performance due to the low infiltration and generally deeper water tables. Preliminary modeling showed that worker exposures and human intrusion scenarios strongly dominate the comparative dose assessments due to direct exposures to the receptors in these analyses. The robust design of the RCRA-C units can exert a significant counterbalance to the limitations imposed by the direct exposure scenarios however. Determining permissible waste concentrations for use in rule making or guidance for this potential disposal option will consider site restrictions, waste form requirements and other factors before decisions are made on final criteria.

1. INTRODUCTION

The management and disposal of radioactive wastes in the United States is governed by a complex and cumbersome number of regulations at the state and federal levels that often result in inconsistent management and regulatory controls. The situation is particularly acute for low-level radioactive wastes since the waste classifications in these regulations are based primarily on the origin of the materials, rather than their specific radioisotope contents and the actual risks they pose to public health and safety and the environment. Some radioisotope bearing materials are not regulated, typically naturally occurring radioactive materials, which may in practice, pose greater risks to the public than some low-activity materials that fall under specific regulations. The low-level waste disposal situation in the United States was evaluated by the National Research Council (NRC), and their report [1] urged that waste management and disposal practices move in the direction of risk based classifications and disposal practices. Currently disposal of low-activity wastes (LAW) is difficult under the existing regulatory framework, particularly for small volume waste generators who cannot take advantage of lower cost options available to large volume generators. The number of licensed low-level waste disposal facilities is low and access is not open to wastes originating from any place in the nation, but rather to members of "compacts" established by the States to secure disposal capacity for their respective waste generators. While there appears to be no immediate problem with disposal capacity [1], very large volumes of low activity waste, potentially generated by reactor accidents of the magnitude of the Fukushima event in Japan or potential terrorist events involving radiation disposal devices (RDD), could easily overwhelm the existing disposal capacity.

To ease some of the difficulties with low-level waste disposal, the Agency has been investigating the potential of using RCRA-C waste disposal technology for disposal, because these disposal cells are constructed with engineered barriers designed to limit infiltration of ground waters into the disposal cells and to minimize releases below the cells. The construction of these disposal units is very similar to, and in some ways more robust than, the construction techniques used for the shallow land burial of low-level radioactive wastes governed by The Nuclear Regulatory Commission (NRC). In 2003, the Agency published an Advanced Notice of Public Rulemaking [2] describing an approach for assessing the performance of these RCRA-C disposal cells for the containment of low-activity wastes (limited to waste concentrations at or below the Class A limits given in NRC regulations (10 CFR Part 61). This paper describes the performance assessments done to assess the containment capabilities of RCRA-C disposal cells and calculate waste concentration limits for disposal that would serve as criteria for classifying a particular waste as a "low-activity" waste.

To implement the RCRA-C disposal technology in practice, two approaches are possible – promulgate standards through the rule making process or issue Agency guidance on disposal implementation practices. The Agency has not finalized on one of these alternatives as yet. Each option has its advantages and limitations. RCRA regulations do not explicitly address the disposal of radioactive materials but do not explicitly prohibit the option either. Some states have regulations that expressly prohibit the co-disposal of radioactive wastes with hazardous materials, and in these states the RCRA-C option would be prohibited. In those situations, rule making would create some potential ambiguity with respect to the prevailing authority and implementation difficulties. Guidance, in contrast, lacks the force of rulemaking, but may be more acceptable to a wider range of affected stakeholders. The Agency continues to seek input on these alternatives before proceeding with either. In any event, waste concentration limits derived from performance modeling of the RCRA-C disposal technology is essential input for either alternative, and needed so that waste generators would be able to determine if particular waste streams could qualify for the disposal option.

2. PERFORMANCE ASSESSMENT APPROACH

The term "low-activity" waste is not defined in existing regulations, in contrast to the Class A, B and C, and Greater-than-Class – C waste classifications given in NRC's 10 CFR Part 61 regulation. EPA's intent is that the wastes potentially qualifying for disposal using the RCRA-C technology would be a subset of Class A wastes, which we are defining as "low-activity" wastes. The allowable concentrations in LAW would be determined by a set of dose/risk assessments. These allowable concentrations are termed Waste Concentration Criteria (WACs) and are calculated by setting up an inverse problem for the performance assessments. In this approach, a fixed uniform radionuclide concentration for each of the radionuclides under consideration is used initially as the source term in the disposal cell, and the dose to a defined receptor is calculated under a range of climate and hydrologic settings. By assuming a fixed allowable dose limit, a unit radionuclide concentration initially and a linear response between the source term release and the receptor dose calculation, the concentrations limits (WACs) in the wastes are simply calculated from the projected doses in the assessments.

There are three sets of exposure assessments involved in determining WACs that would be used for implementing the disposal option: (1) the expected case and variations; (2) human intrusion scenarios and; (3) worker exposures. The expected case involves the slow degradation of the disposal cells and failure mechanisms which would result in the release of radionuclides into the subsurface, downward movement into the saturated zone and subsequent migration to off-site wells and exposures to individuals using the ground waters. The expected case examines performance under a wide range of climate and hydrogeologic settings to capture the range of possible geographic locations where disposal cells may be located. With a large range of situations it is also possible to perform assessments using high-end values of some parameters, such as infiltration, depth to ground water, that may represent "off-normal" conditions and allow sensitivity analyses to be performed to identify "driver" parameters which may dominate the exposure assessments. Human intrusion scenarios are important for several reasons. The RCRA-C and NRC licensed low-level shallow land burial sites are near-surface facilities, and as such inadvertent intrusion cannot be eliminated at some point in the future when institutional controls cannot be assumed to be in place. Also, the waste classification in NRCs Part 61 regulation was based on human intrusion exposure assessments. Lastly, we have assumed that the handling, treatment, storage and transportation of these low-activity wastes would be done in a similar fashion to hazardous waste management operations. Assessing exposures to workers would provide another control on WACs for implementation and may contribute to defining recommended operating practices to minimize exposures, particularly if the Agency guidance route is chosen. WACs would be calculated for each of these three classes of exposure assessments and compared to determine limiting values for each radionuclide under consideration.

3. THE EXPECTED CASE

The design of a RCRA-C disposal cell is intended to minimize infiltration of ground waters into the waste containment area and also allow monitoring it's containment performance via a leachate collection system that allows collection of leachates during the active custodial operations period. No long-term performance information is available to judge the efficacy of the design simply because these units have not been in operation long-enough for the active controls to be lifted. To model the performance of these units over long time frames (hundreds to thousands of years) some conservative simplifying assumptions are necessary along with some assumed failure modes, as described below.

3.1 RCR-C disposal cell design and failure modes for assessments

The expected case assessments examine two failure modes for the RCRA-C disposal cell design, which consists of a multilayered cap over the emplaced wastes designed to limit infiltration from precipitation and a liner system below the wastes. The cap must have a soil covering capable of supporting vegetation to minimize erosion potential and underlain by a drainage layer intended to divert rainfall infiltration away from the disposal cell. A high-density synthetic material is located below the drainage layer and over a clay base at least 2 ft. thick with a hydraulic conductivity of less than 10^{-7} cm/sec. Backfill material is placed around the wastes in the disposal unit. The sides and bottom of the disposal unit consist of a double composite liner system comprising a clay layer with the same conductivity as above and synthetic materials. A leak detection/leachate collection system is installed between the liner's synthetic layers directing leachates to a sump for removal. These features are shown in Figs 1 & 2.

The failure mechanisms assumed for release modeling involve cap failure and sump failure modes. For the cap failure mode, the sides and bottom liners are omitted in which case infiltration goes directly into the emplaced wastes and into the subsurface. For the sump failure, leachates are directed to the sump which is assumed to be no longer actively maintained or sealed to prevent leakage, and leachates can then go directly to the saturated zone, bypassing the unsaturated zone. The two failure mechanisms result in transport of releases into the saturated zone across the entire area under the disposal unit (the cap failure release mode), or a point source (the sump failure release mode). As a conservative assumption, the retardation potential of the liner materials is not taken into account, but some additional analyses were performed for selected radionuclides to estimate the magnitude of conservatism resulting from the assumption.

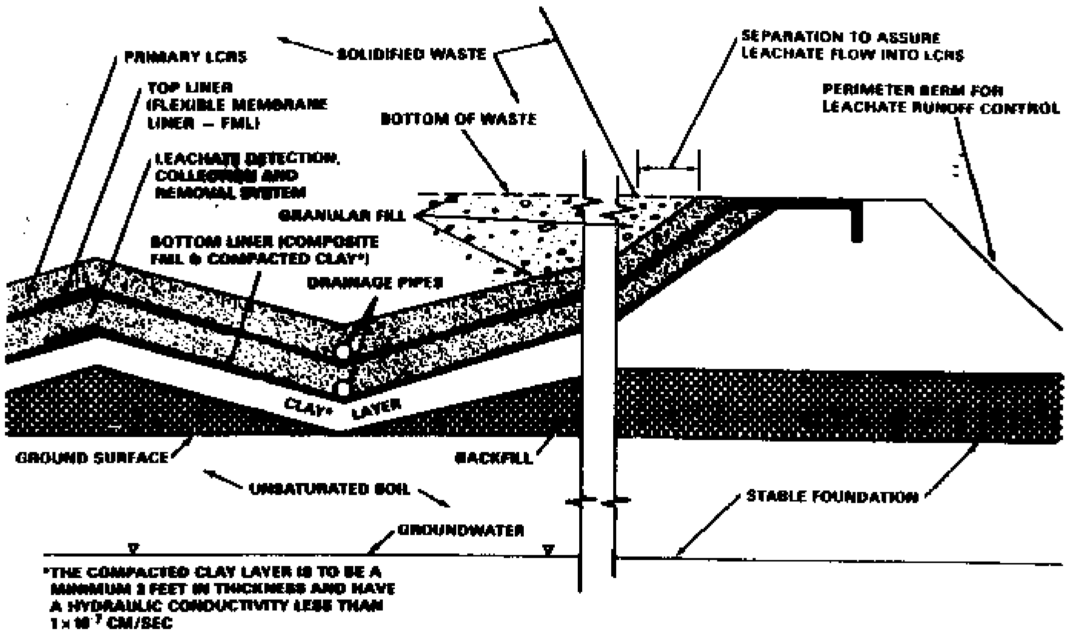

Figure 1 RCRA-C liner design

3.2 Codes for the expected case exposure modeling

The exposure modeling was performed with a combination of codes designed to address portions of the total disposal system and transport pathways. Releases of radionuclides within the disposal unit (the near-field) were modeled with the DUST-MS code [3][4]. This code is a finite difference model for the waste unit and capable of addressing multi-species release and transport within the unit. The DUST-MS code assumes reversible equilibrium partitioning between solid and liquid phases, an unconsolidated homogeneous material in the disposal cell, zero boundary concentration at the unit surface and zero concentration gradient at the bottom along with first order losses for transformation processes. While these assumptions form a simple description of the interior of the disposal cell for modeling calculations ease, there is little alternative recognizing the inherent uncertainties in the actual characteristics, configurations and backfill variations likely in reality within the disposal cells. The DUST-MS model provides input data to the far-field flow and transport model.

For transport from the bottom of the disposal cell, through the unsaturated zone, into the saturated zone and down-gradient to an off-site well, the EPACMTP model [5] [6] was used. The unsaturated zone module in EPACMTP assumes steady-state or variable, one-dimensional vertical flow (advection and dispersion) below the source to the water table. No mass transfer to soil gas, and upward mass transport, is allowed, making the mass transfer calculations for tritium and carbon-14 conservative.

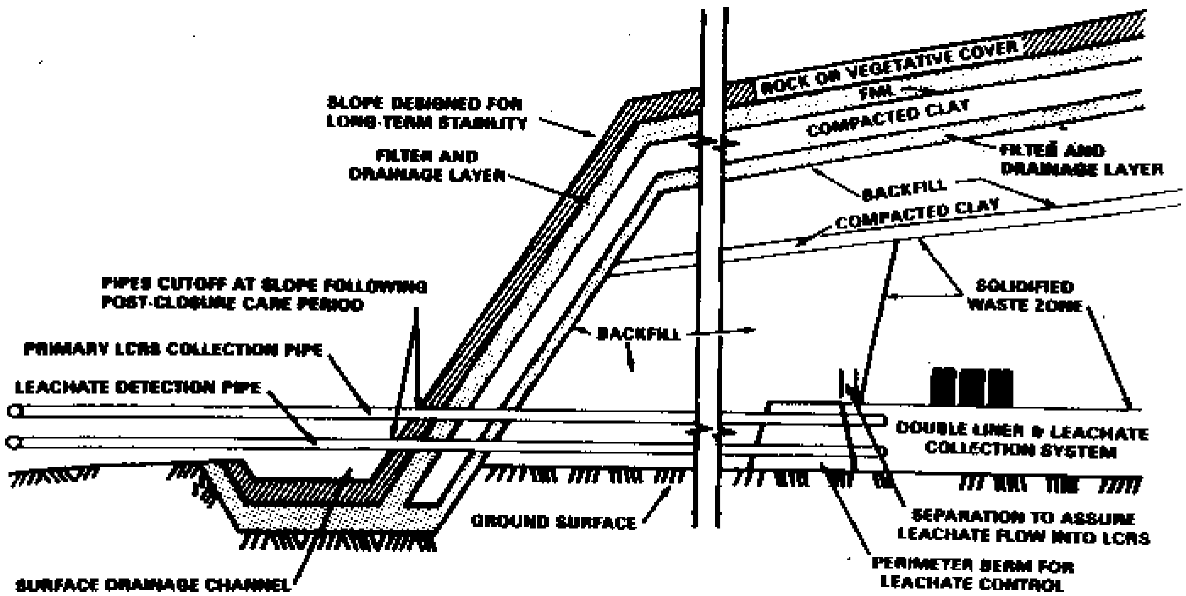

Figure 2 RCRA-C cover design

In the saturated zone, EPACMTP can address steady-state or variable three-dimensional flow in an unconfined aquifer including advection, dispersion and retardation/degradation of the contaminant. The degradation capability allows radioactive daughter calculations to be made. The code allows multiple depth data collection for contaminants reaching the off-site well, which was assumed to be located at the center of the contamination plume and sampled at eleven depths within the aquifer. To handle radionuclide chain decay calculations and integrate the well data, additional capabilities were added to EPACMTP to handle multiple breakthrough curves and averaging the breakthrough curves for the well contaminant concentrations over time. The EPACMTP code contains a database of aquifer characteristics (e.g., depth to ground water, aquifer thickness hydraulic gradient and conductivity) for sampling during realizations.

For the biosphere exposure pathways, the averaged well water contaminant concentrations were used as input to spreadsheet format calculations for various exposure pathways from food ingestion as functions of contaminate water concentrations. The calculations were based on the relationships in the RESRAD family of codes and parameter distributions were taken from published sources [7][8][9].

To operate this three-part linkage efficiently (DUST-MS, EPACMTP and RESRAD spreadsheet), a wrap-around module titled MC-DUST was created, tested and verified to link the codes and spreadsheet calculations. MC-DUST contains a Monte Carlo sampling module to prepare input files for execution by DUST-MS and take the output for insertion into the ground water model (EPACMTP), as well as integrate Monte Carlo hydrologic parameter selections made within EPACMT data bases.

For a single realization, a set of site input data must be generated with MC-DUST. Input data for precipitation and infiltration over the RCRA-C cell were sampled from EPA's HELP data base, a compilation of precipitation and soils types developed of RCRA-D landfill locations [10][11]. These data were used because they cover a wide range of climate and hydrologic settings across the United States. The input data sampled by MC-DUST is input to the waste unit near-field model (DUST-MS) and calculations of releases are made for two types of waste forms (cement and non-cement waste forms). Radionuclide breakthrough data are then formatted by MC-DUST and given as input to EPACMTP, which then performs flow and transport calculations along the ground water path to the off-site well. The contaminant concentrations reaching the well are averaged and given as input to the spreadsheet calculations for doses to the receptor, which are also done by sampling parameter distribution values. WACs are back calculated for each realization using the initial input waste concentrations (1 pCi/gm), the doses received by the receptor and the defined maximum dose, assuming a linear relationship between initial waste concentrations and projected doses. Since a probabilistic approach is used in data selection, the calculated WACs are associated with the probability of occurrence, e.g., a WAC level can be designated as resulting in 90% of the receptor doses being below the defined dose limit

3.3 Expected case scenario assumptions

For the expected case realizations, a number of defining assumptions were made. The defined dose limit to the off-site receptor was 15 mrem/yr.; a value selected simply to be consistent with the dose limit for radioactive waste disposal in geologic repositories. The off-site well was located 150 meters beyond the disposal unit boundary. The receptor was assumed to be a resident drinking contaminated well waters and consuming some food, both meat and vegetables, raised using contaminated waters. Two climate conditions were used; arid and humid climates and data selected accordingly from the HELP and EPACMTP site parameter values data bases. In the disposal cells two types of waste forms were assumed and analyzed independently, cement waste forms and non-cement forms. Cement was examined because it's typically used as an immobilizing media and it strongly affects the pH of the disposal unit infiltration waters (typically giving pH ranges of 10 -14) which in turn has a significant effect on the sorptive and solubility behavior of some radionuclides and the Kd values selected for retardation modeling both in the disposal unit and in the subsurface. Radionuclides with half-lives less than 2 yrs were not examined under the assumption that active institutional controls (probably several decades) would assure that there were no off-site releases, and after active controls ended there would be a time period of additional decades before the disposal unit would degrade sufficiently for the failure modes to occur. This is a very conservative assumption in that the robust engineering of the disposal cell and likely prohibitions against disposing of highly mobile liquid wastes would assure that at least 100 years of containment would be likely. Over time the hydraulic conductivity of the cap was allowed to degrade to adjacent soil levels over a period of three hundred years. The modeling time frame of interest was 1,000 years, although realizations were extended to 10,000 years to determine when some contaminants would eventually reach the well. Considering the disposal units are near-surface facilities, it appears unreasonable to assume they would resist significant erosive damage beyond a thousand years.

4. HUMAN INTRUSION EXPOSURE ASSESSMENTS

Since the potential of an intrusion is impossible to eliminate, exposure assessments for intrusion scenarios must be examined in the course of developing WACs. We have examined three intrusion scenarios, derived from typical intrusion scenarios described in the literature. The scenarios assess exposures resulting from drilling through an abandoned disposal unit, from construction of a residence on an abandoned disposal unit and, exposures resulting from a resident part-time farmer lifestyle where contamination is derived from the use of contaminated ground water used for farming activities. For all of these analyses the exposure pathways include inhalation, ingestion and external exposure, with the specific details tailored to the receptor's potential exposures in each scenario. Since the intrusion time cannot be forecast with any certainty, three times after facility closure were examined, 100, 300 and 500 yrs. The code used for the assessments was RESRAD–ONSITE, simply because of its wide spread use and easier acceptance within the risk assessment community. Since the assessments of RCRA-C disposal performance cover a wide range of climate and hydrogeologic situations across the United States, tailoring receptor lifestyle characteristics to specific locations is impractical and therefore generic values were selected for biosphere pathways parameters. Parameter values were taken from published sources used for the biosphere modeling in the expected case. A fixed receptor dose for these assessments was set at 500 mrem/yr. This was done for consistency with the exposure assessments done by NRC in deriving the waste classifications in 10 CFR Part 61.

For the home construction scenario, a construction worker would excavate a house foundation over the disposal cell to a depth of three meters, with a total excavated volume of 906 m^2 and a dilution factor of 0.41 from mixing the contaminated materials with overlying sols [12]. The worker is assumed to inhale 480 mg/day of contaminated soils and the construction time was varied between 100 and 500 hours.

For the drilling scenario, the volume of excavated contaminated material was assumed to be 0.78 m^3 [12] with dilution factors of 0.12 and 0.42 for arid and temperate climatic conditions. Soil ingestion was assumed to be 480 mg/day, with a total exposure time of 6 hours [12]. From these values it is evident that the drilling scenario will result in significantly less exposure to the receptor than the construction worker scenario.

The most conservative exposure scenario is the post-construction agricultural resident, where exposures result from excavated materials distributed in the area surrounding the constructed house, use of contaminated water for drinking and farming activities with exposures from ingestion of meat and vegetables grown using the contaminated well waters. The resident agricultural receptor is assumed to reside in place for 50 yrs., spending half–time at the residence and the rest of the time off-site. Approximately 25% of the receptor's food is assumed to be contaminated. This is not a subsistence farmer scenario, because that scenario is unlikely in the U.S., and represents an unreasonably conservative situation. Disposal facilities are not likely to be sited on high-value agricultural land. Results for the intrusion scenarios are discussed below.

5. **WORKER EXPOSURE** ASSESSMENTS

Since the RCRA-C disposal option involves the use of hazardous waste disposal units, examining the potential exposures to workers in hazardous waste storage and treatment facilities from the handling of low-activity radioactive wastes is appropriate to assure potential exposures are within acceptable ranges. For these assessments, time/motion studies of operations at hazardous waste treatment facilities were used to develop scenarios for various worker exposures. The worker assessments included: stabilization workers (two types) involved with treating incinerated and as received wastes by solidification; waste handlers (two types) performing sampling, storage and transportation functions as well as disposal on-site; an equipment operator performing burial, mixing and other activities with fork-lifts and back-hoes both in the facility and for on-site disposal. Two truck driver exposure assessments were performed for situations where wastes are transported in either liquid or solid form.

The major pathways for worker exposure at these facilities are dust inhalation and external exposure. Workers in treatment and storage facilities were assumed to wear protective respirators with established protection factors, and to spend half their time handling or in the vicinity of the wastes. Dust loadings were assumed to be the same as those measured in the hazardous waste handling facilities. Internal exposures were calculated by assuming equivalent ingestion amounts of contaminated dust as estimated for the hazardous waste treatment workers and by use of published dose conversion factors. For external worker dose assessments, solid wastes were assumed to be in 55-galon drums and exposure times were calculated assuming normal annual working hours over a twenty year period. For the storage and transportation workers, external doses from sealed waste drums in conservative configurations were calculated using the Microshield code. Exposure times were calculated assuming the drivers spend the maximum allowable time on the road and sleep in cabs attached to the trucks. These are conservative assumptions since sleeping close to the wastes will likely be discouraged in practice. Results of the assessments are discussed below.

6. RESULTS OF EXPOSURE ASSESSMENTS

The results of the assessments are discussed below along with the results of some sensitivity analyses to determine "driver" parameters and their implications for the RCRA-C disposal option implementation.

6.1 Expected case assessment results

The most striking result of the expected case assessments is the superior performance offered by disposal sites in arid climate areas. Under arid conditions only the most mobile radionuclides (I-129, Tc-99, C-14, H-3) reached the well within the 10,000 year modeling timeframe for the cap failure scenario, which releases a higher mass of radionuclides to the subsurface than the sump failure scenario and does not ignore the unsaturated zone below the disposal unit. For an arid disposal site, WACs based on performance of the disposal cell would be largely limited by the Class A radionuclide levels except for the highly mobile species. For the humid settings, the performance is, as expected, less dramatic. At the 90th percentile level for the cap failure mode, some radionuclides still did not reach the well during the modeling period (Sb-125, Cd-109, Cs-134,137, Co-60, Fe-55, Pb-210, Pm-147, Pu-238, Ra-228, Sr-90). For the sump failure mode at an equivalent level all the modeled radionuclides reached the well although for most of the radionuclides that did not reach the well for the cap failure mode the amounts reaching the well for the sump failure mode were relatively small. No consistent trend was seen in the WACs derived for individual radionuclides in either the cement of non-cement waste forms, probably due to the individual variations of sorption behavior affected by the pH alterations caused by reaction with the degrading cement.

Sensitivity studies for the expected case show positive correlations between receptor doses and some hydrologic parameters, notably hydraulic conductivity and longitudinal dispersion as well as Kd values for sorptive radionuclides. For highly mobile radiouclides with relatively little sorption along the travel path, hydraulic properties and infiltration rates through the cap and the emplaced wastes appear to have a strong control on concentrations reaching the well in the humid climate situations as well as for the arid site transport. The effects of hydrologic properties on the calculated concentrations are similar for both the cement and non-cement waste forms.

The assessments of expected case performance have some significantly conservative assumptions embedded in them. One conservatism in particular is the assumption that the bottom liner material exerts no retardation effects in the transport calculations. To assess the degree of conservatism in that conservative assumption, a group of four radionuclides with varying Kd values were examined (ranging from H-3 with Kd=0, to Ra-226 with Kd = 7.05 E+04) by taking sorptive credit for the liner. For the low Kd radionuclides no significant effect was observed. In contrast the WAC for the strongly adsorbing Ra -226 increased 17 orders of magnitude. This suggests strongly that radioisotopes such as cesium, which has a strong adsorption on illitic clays, will in practice show lower releases than the modeling would indicate.

6.2 Human intrusion assessments

In contrast to the deterministic analyses performed by the NRC for the intrusion scenarios used to derive the Part 61 waste classifications, our analyses were done probabilistically. In consequence the mean values for the exposure assessments for the scenarios were used to determine limiting WACs and for comparison with the NRC waste classification limits. For the intruder assessments, the resident agricultural scenario is the most restrictive. The driller and house construction workers can experience significant doses, but the relatively short exposure duration results in lower doses over time in comparison to the post-construction resident who also consumes food grown with contaminated well waters and soils spread around the residence after construction. As expected, the dose levels decline as the time of the intrusion increases from 100 to 500 years after disposal cell closure. Sensitivity assessments were performed and gave results unique to the particular scenario. For the driller scenario, exposures were sensitive to the size of the contaminated cuttings disposal pile. For the construction worker, the excavated waste content and soil dilution factor had significant effects on exposures. For the limiting scenario, the post-construction resident radon pathways through the residence had a significant effect on exposures along with the indoor time fraction and soil contamination levels.

6.3 Worker exposure assessments

Results of the worker assessments indicate that the stabilization and waste handler workers as the limiting cases. These results are not surprising because these workers are in closer proximity to the untreated wastes before stabilization and during solidification processes. Sensitivity analyses indicate that the controlling parameters are distance between the source and receptor, dust loading, annual exposure time and shielding thickness. While distance between the wastes and the processing workers may not be easily changed, to minimize exposures workers should wear efficient respirators when in proximity to untreated waste materials and have adequate shielding whenever possible. Shielding is particularly important for minimizing exposures from proximity to drums containing wastes. The configuration of drums used in the external exposure analyses were deliberately selected to give higher exposures, i.e., the worker was placed directly at the center line of drum aggregations (the Z coordinate of the drum array). Moving waste drums while keeping the workers away from the center of the drums greatly reduces external exposure rates.

These assessments for storage, treatment and disposal workers have some parallels to the situation faced by clean-up workers responding to an RDD event. In both situations, exposures will be dominated by dust inhalation and external exposures as well as duration of the activities. For the RDD worker, dust inhalation levels and direct exposure rates may be higher, but the duration of exposures will probably only last for weeks to months as opposed to the twenty years assumed for the facility workers. For the RDD worker, efficient respirators and shielding are strongly recommended to reduce exposure levels.

7 CONCLUSIONS

The end point for the exposure modeling is to determine waste acceptance criteria for the disposal of low-activity wastes in RCRA-C disposal cells. The preliminary exposure modeling described above serves as the first step in determining the WACs for incorporation into either rule making or guidance to assist waste generators and treatment/storage/transportation and regulatory authorities to implement the disposal option. Table 1 below lists the limiting scenarios for various radionuclides that may be in low-activity wastes. By limiting WACs we mean the exposure scenario that gives the lowest WAC level for the defined dose used in the assessments. For the worker exposure assessments that represents the most likely WAC for a 25 mrem/yr dose, for the expected case this represents the sump failure scenario under humid conditions at the 50th percentile with a 15 mrem/yr dose limit, and for the human intrusion scenario this represents the 100 year intrusion scenarios with a receptor dose of 500 mrem/yr.

The results given below do not represent final WACs for implementation but rather preliminary assessments to serve as a starting point for deciding what exposure limits should be used in setting the final WACs that would appear in regulatory documents, either rule making or guidance. In determining the implementation WACs, consideration must be given to the relative levels of uncertainty in the data and assessments performed, as well as consideration to the degree of conservatism inherent in the assessments. While all the assessments contain conservative elements, as they should, the degree of conservatism must be evaluated against judgments about their application to actual implementation. As mentioned previously, the expected case modeling took no retardation credit for the clay liner materials below the wastes. The liner is a required design element for the RCRA-C disposal cell and in practice some significant retardation would be expected for radionuclides showing an affinity for sorption on clays, such as Cs on illitic clays. Design requirements mandating the use of illitic clays would provide better performance and consequently a higher WAC could be assigned than would otherwise considering only the results of the modeling exercise.

As another example of the considerations that would go into defining the WACS, the expected case shows that disposal units in arid regions show superior performance over the modeling period, due to the limited infiltration and depth to ground water. In formulating implementation WACs, the possibility of having separate WACs for arid versus humid settings is appealing to avoid the situation where implementation is very limited because the WACs are driven to low levels by the "worst case" disposal unit performance situation. Another consideration in finalizing the WACs is the relative weight that should be given to limits derived from worker exposure assessments and the highly speculative human intrusion scenario assessments in comparison to the performance based limits which are the more likely situation. Modifications to worker operational procedures could easily change the WACs by drastically lowering occupational doses, or assuming higher allowable occupational doses in comparison to the levels used in the worker assessments reported here.

Table 1 Limiting Scenarios and LAW WACs from Scenario Modeling

Radionuclide	Limiting WAC (pCi/g)	EPA Limiting Scenario	NRC Class A Limit (pCi/g)	Radionuclide	Limiting WAC (pCi/g)	EPA Limiting Scenario	NRC Class A Limit (pCi/g)
H-3	3.63E-03	EC	2.42E+07	Pm-147	5.32E+05	WE	4.24E+08
C-14	2.89E+02	EC	4.85E+05	Hg-203	1.10E+06	WE	4.24E+08
Na-22	2.66E+05	WE	4.24E+08	Ra-226	3.91E+01	HI	No Limit
S-35	1.88E+06	WE	4.24E+08	Ra-228	9.96E+02	WE	No Limit
Ca-45	9.65E+05	WE	4.24E+08	Th-228	6.61E+01	WE	4.24E+08
Mn-54	1.68E+06	WE	4.24E+08	Th-229	3.69E+01	WE	No Limit
Fe-55	6.78E+06	WE	4.24E+08	Th-230	1.88E+02	WE	No Limit
Co-57	4.78E+06	WE	4.24E+08	Th-232	1.06E+02	WE	No Limit
Co-60	3.36E+01	WE	4.24E+08	U-232	1.00E+03	HI	No Limit
Ni-63	2.96E+06	HI	2.12E+06	U-234	7.55E+02	WE	No Limit
Zn-65	1.62E+06	WE	4.24E+08	U-235	8.50E+02	WE	No Limit
Sr-90	1.67E+04	HI	2.42E+04	U-238	9.19E+02	WE	No Limit
Tc-99	6.26E+02	EC	1.82E+05	Pu-238	5.68E+01	WE	1.00E+04
Cd-109	3.97E+05	WE	4.24E+08	Pu-239	5.24E+01	WE	1.00E+04
Sb-125	2.31E+02	WE	4.24E+08	Pu-241	2.91E+03	WE	3.50E+00

Radionuclide	Limiting WAC (pCi/g)	EPA Limiting Scenario	NRC Class A Limit (pCi/g)	Radionuclide	Limiting WAC (pCi/g)	EPA Limiting Scenario	NRC Class A Limit (pCi/g)
I-129	7.02E+00	EC	4.85E+03	Pu-242	5.52E+01	WE	1.00E+04
Cs-134	3.92E+05	WE	4.24E+08	Am-241	6.30E+01	WE	1.00E+04
Cs-137	1.59E+02	WE	6.06E+05	Am-243	2.82E+03	HI	1.00E+04
				Sm-147	4.55E+04	HI	No Limit

REFERENCES

[1.] National Research Council, "Improving the Regulation and Management of Low-Activity Radioactive Wastes", National Research Council of the National Academies, 2006, National Academy Press

[2.] EPA, "Approaches to an Integrated Framework for Management and Disposal of Low-Activity Radioactive Waste: Request for Comment; Proposed Rule", 2003, Federal Register, Vol. 68, No. 222, pp 65119-65151, Tuesday, November 18, 2003.

[3.] Sullivan, T.M., "DUST-MS-D, Disposal Unit Source Term, Multiple Species, Distributed Container Failure, Data Input Guide", 2002

[4.] Sullivan, T.M., "Selection of Models to Calculate the LLW Source Term", NUREG/CR-5773, BNL-NUREG-52295, (US Nuclear Regulatory Commission, Washington, D.C.), 1991

[5.] EPA, U.S. Environmental Protection Agency, "EPA's Composite Model for Leachate Migration with Transformation Products, Background Documents for EPACMTP: Metals Transport in the Subsurface, Volume 1: Methodology" 1999 EPA/402-R-99-001, Office of solid Waste, Washington, D.C.

[6.] EPA/SAB, U.S. Environmental Protection Agency/Science Advisory Board, "An SAB Report: Review of EPA's Composite Model for Leachate Migration with Transformation Product- EPACMTP" 1995, EPA-SAB-EEC-95-110, August 1998.

[7.] Beyeler, W.E., Hareland, W.A., Duran, F.A., Brown, T.J., Kalinina, E., Gallegos, D.P., and Davis, P.A., "Residual radioactivity from decommissioning: parametric analysis", 1999, NUREG/CR-5512.

[8.] NCRP (National Council on Radiation Protection and Measurement), "Recommended screening limits for contaminated surface soil and review of factors relevant to site-specific studies", 1999, NCRP Report 129.

[9.] Yu, C., LePoire, D., Gnanapragasam, E., Arnish, J., Kamboj, S., Biwer, B.M., Chang, J.J., hen, S.Y., "Development of probabilistic Resrad6.0 and Resrad build 3.0 computer codes", 2000, NUREG/CR-6697.

[10.] Schroeder, P.R., Morgan, J.M., Walski, T.M., and Gibson, A.C., "The hydrologic evaluation of landfill performance model (HELP): Volume 1 – Users Guide for Version 1 and Volume II –Documentation for version I", 1984, EPA/530-SW-84-009, U.S. Environmental Protection Agency, Washington, D.C.

[11.] Schroeder, P.R., Dozier, T.S., Zappi, P.A., McEnroe, B.M., Sjostrom, J.W., and Peton, R.I., " The hydrologic evaluation of landfill performance model (HELP): Engineering Documentation for Version 3", 1994, EPA/600/R-94/1686, U.S. Environmental Protection Agency, Washington, D.C.

[12.] Oztunali, O.I., and Rhodes, G.W., ""Update of the Part 61 Impacts Analysis Methodology", 1986, NUREG/CR- 4370, Vol.1, U.S. Nuclear Regulatory Commission.