INFLUENCE OF LEACH RATES AND OTHER FACTORS ON GROUNDWATER MIGRATION

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During the comment period following the publication by the Nuclear Regulatory Commission (NRC) of the proposed rule 10 CFR Part 61, comments were received on the impacts analyses methodologies utilized. Some of these comments addressed the groundwater migration methodologies in general, and the assumed leach rate characteristics of the wastes in particular. These comments suggested that essentially all waste which must be stabilized according to the stabilization requirements in the draft Part 61 rule should be stabilized by means of solidification. One comment also proposed the establishment of specific leach rate standards for such solidified waste. This paper addresses these issues and analyzes the influence of leach rates of solidified waste and other factors on groundwater migration of radionuclides.

INTRODUCTION

In order to help provide input into the issues raised on the proposed rule 10 CFR Part 61 (Ref.1) and the accompanying draft environmental impact statement (EIS) (Ref.2), and to assist in the preparation of the final Part 61 EIS and rule (Refs. 3,4), NRC contracted with the firm of Dames & Moore. One of the products of this contract was a report entitled "Influence of Leach Rate and Other Parameters on Groundwater Migration" (NUREG/CR-3130) (Ref. 5). This paper is a summary of this work and report.

In reference 5, a sensitivity analysis is performed in which the leaching characteristics of selected low-level radioactive waste streams are varied, and the resulting potential human exposures due to groundwater migration calculated, as a function of alternative disposal facility designs and operating practices. This analysis is also performed to assess whether a leaching standard for solidified waste streams is necessary to ensure safe disposal of low-level waste. To perform the analysis, some computer codes are created which are derivatives of the impact analyses codes developed for the draft and final Part 61 EIS.

The general approach to evaluating the potential groundwater impacts resulting from varying the leaching rate of solidified waste consists of the following steps:

(1) Development of a generic waste spectrum based on radioactive wastes expected to be routinely generated in the near future;
(2) Variation of the leaching properties of applicable waste streams within this generic spectrum;
(3) Variation of the disposal technologies that will be utilized to dispose of these wastes; and
(4) Variation of the environmental properties of the location at which the waste will be disposed.

In the remainder of this paper, each of the above four steps are discussed in turn. Following this, a brief discussion is presented of the mathematical formulation of the groundwater migration model, along with some apparent implications of the model. Finally, some results of the study are presented, followed by the principal conclusions.

Generic Waste Spectrum

Low-level radioactive waste exists in a very wide range of types, forms, and activities. To enable decisions regarding waste disposal to be made for the Part 61 regulation, a radioactive waste source term was developed in which this range was characterized in terms of physical, chemical, and radiological properties. This was accomplished by identifying and aggregating all the various types and forms of low-level waste expected to be generated from 1980 to the year 2000 into a managable number of groups, called "waste streams." A total of 37 waste streams were considered for the final EIS, and each waste stream represented a particular type of waste such as pressurized water reactor ion-exchange resins, compacted trash, various medical wastes, etc. In the mathematical model describing groundwater migration, the impacts resulting from disposal of each of the waste streams was considered in turn, and then the total impacts from all waste streams summed. This allowed the particular physical, chemical, and radiological characteristics of each waste stream which contribute to groundwater migration to be considered independently.

The volumes and physical, chemical, and radiological characteristics of each waste stream could vary depending upon the particular waste processing alternative chosen, and upon alternative regulatory requirements (e.g., alternative waste classification requirements). This variation was necessary for the purposes of the Part 61 EIS, but was too complex for this sensitivity analysis. To enable the cases considered in the sensitivity analysis to be compared on a meaningful basis, a generic waste spectrum was developed from the 37 waste streams using the following three-step procedure:

(1) The reference waste distribution was assumed to be processed according to typical existing industry practices and then classified according to the requirements in the final Part 61 rule.

Class B and C light water reactor (LWR) ion-exchange resins and filter sludge are assumed to be solidified. Class A ion-exchange resins and filter sludge are dewatered while LWR concentrated liquids are solidified. Class B and C activiated metal waste streams are stabilized by filling interstitial voids in a waste container with a noncompressible solid. Most other waste streams are packaged in a structurally unstable manner.

(2) Following classification, the portion of the classified waste distribution determined to be unacceptable for near-surface disposal is removed from further consideration. That is, the above waste classification procedure is only performed once, and the inventory of radionuclides determined to be contained in each waste class is held constant for all the cases in the analysis.

(3) The classified waste streams are regrouped into 12 "macro streams" which have similar characteristics in terms of groundwater migration considerations. For example, waste form properties such as whether or not a waste streams is in a stable form, the particular stabilization method used (if any), and whether the waste stream contains chemical agents will have an influence on the calculated results.

The physical and chemical characteristics of the individual waste streams are tracked by assigning each waste stream a particular set of integer indices, called "waste form indices." These indices are used to trigger a particular calculational procedure in the analysis. In this study, the indices considered included the following:

Leachability index (I6)
I6 = 1: unsolidified waste
I6 = 2: cement solidification
I6 = 3: synthetic polymer solidification
I6 = 4: an optimistic solidification procedure

Chemical content index (I7)
I7 = 0: does not contain chelating agents or organic chemicals
I7 = 1: contains chelating agents or organic chemicals

Waste stability index (I8)
I8 = 0: structurally unstable waste form
I8 = 1: structurally stable waste form

Accessibility index (I9)
I9 = 1: readily accessible
I9 = 2: moderately accessible
I9 = 3: accessible with difficulty

Most of the indices are self explanatory. The accessibility index is used to describe unsolidified materials such as activated metals in which radionuclides are bound up within a matrix and are released for groundwater migration through a corrosion rather than a leaching mechanism.

Variation of Leaching Properties

A very important consideration is that only four of the 12 waste streams thus created are suitable for solidification. These four waste streams consist of LWR concentrated liquids and Class B and C ion-exchange resins and filter sludge. The remaining streams -- e.g., compacted trash -- are not considered generally suitable for solidification. In each case considered, therefore, the four waste streams "suitable for solidification" are assumed to be submitted to four optional solidification scenarios, termed the base, cement, synthetic polymer, and optimistic scenarios. The leaching characteristics and volumes of the four waste streams suitable for solidification changes for each solidification scenario considered. The volumes and leaching characteristics of the other eight macro streams are fixed throughout the analysis.

Variation of Disposal Technologies

There may be many ways in which low-level waste may be disposed, and the analysis methodology considers the effect of different disposal technologies on groundwater migration. These different disposal technologies were characterized for analysis in the Part 61 EIS. In this paper, waste is assumed to be disposed into standard shallow land burial facilities, and the operation of the facility is assumed to vary based upon the following options:

Disposal cell covers (IC)
IC = 1: unimproved
IC = 2: improved

Stabilization (IX)
IX = 1: no special compaction measures
IX = 2: improved compaction using industrial equipment
IX = 3: extensive compaction (eg, dynamic compaction)

Waste segregation (IS)
IS = 0: no segregation
IS = 1: stable/unstable waste segregation
IS = 2: chemical/non-chemical waste segregation
IS = 2: both stable/unstable and chemical/non-chemical segregation

Waste emplacement (IE)
IE = 1: random disposal
IE = 2: random disposal with permeable backfill

Similar to the waste streams, these disposal technology options are tracked through the calculational procedures by a set of integer indices, termed "disposal technology indices." The disposal technology indices used in this paper are given above.

Varying these disposal technology indices results in varying (1) the amount of percolation within the disposal cells, (2) the contact time between waste and percolating water, (3) the leaching characteristics of solidified waste streams, and (4) the degree to which migrating radionuclides are retarded by ion-exchange mechanisms. A total of 48 cases (including four solidification scenarios for each case) are generated by varying the above disposal technology indices.

Variation of Site Environmental Properties

Five hypothetical disposal facility sites are considered in the report. The first four of these sites are regional sites developed in the Part 61 EIS for estimating the unmitigated impacts of regional disposal of waste according to the Part 61 requirements. Each of the four regional sites is located within a region which could represent a large multi-state compact formed for waste disposal. These are termed the northeast, southeast, midwest, and southwest sites. The fifth disposal facility is a variation of the southeast regional disposal facility site environmental characteristics assuming reduced groundwater retardation coefficients and faster groundwater travel times to biota access locations.

Variation of the disposal sites considered in the report allows for consideration of the effect of different environmental properties on the results.

MATHEMATICAL MODEL

There are three identifiable components that provide input to the groundwater migration formulation used in this paper. These are the "source term," the "migration model" and the properties of the "biota access location." These components can be seen from the following equation used in the draft and final EIS and in this paper:

$$H_{ij} = (D_{ij}/Q) \sum_{k} J_{oik} \, r_{ik} \qquad (1)$$

where H_{ij} is the calculated dose rate in units of mrem/year to organ j resulting from radionuclide i, D_{ij} is the corresponding pathway dose conversion factor in units of mrem-m^3/Ci-year, and Q is the dilution rate at the biota access location in units of m^3/year. The terms D_{ij} and Q are functions of the properties of the biota access location. The factor J_{oik} is the "source term" in units of Ci/year from waste stream k, while r_{ik} is the corresponding dimensionless migration reduction factor representing the "migration model" component.

The variation of the source term parameters and their effect on the calculated dose rates is discussed below, as is the influence of the migration model component. The influence of the environmental characteristics of the disposal site is also briefly discussed. The dilution rate (Q) and pathway dose conversion factors are discussed in reference 6.

Source Term Variations

The groundwater migration source term, J_o (dropping the subscripts i denoting the radionuclide and k denoting the waste stream), for a particular radionuclide and waste stream is given in units of Ci/year, and can be expressed through the following equation (Ref. 6):

$$J_o = C \, V \, f_c \qquad (2)$$

where

C = the concentration of the radionuclide of concern (in Ci/m^3) in the waste stream considered.

V = annual volume of percolating water entering the disposal cell(s) containing the waste stream, contacting the waste, and leaving the disposal cell(s) to enter the groundwater regime (in m^3/yr).

f_c = reduction in the radionuclide concentration during transfer from the waste to the leachate (dimensionless).

The first term in the above equation, the radionuclide concentration (C), varies depending upon the particular macro waste stream considered. The other parameters in the equation, V and f_c, are functions of the waste stream considered, the disposal site environmental conditions, and the particular set of disposal technology indices.

Furthermore, the following equations apply:

$$V = p \, S \qquad (3)$$

where p is the percolation (in meters/year) that enters the disposal cells occupied by the waste stream and contacts the waste, and S is the total ground surface area above the disposal cells multiplied by the ratio of the waste stream volume to the total waste volume (in m^2).

The percolation, p, is allowed to vary depending upon the disposal technologies considered and the physical and chemical characteristics of the waste stream. It is based upon multiples of two values: p1, computed through a water balance method representing the site conditions prior to establishment of the disposal facility, and p2, computed through darcy velocity considerations representing improved disposal cell covers. The following table presents the variation of the percolation value with waste form and disposal technology considerations.

Cell Stabilization (IX)	Waste Stability (I8)	Percolation Value (p) Segregation Index (IS=0 or 2)	(IS=1 or 3)
Unimproved Cover (IC = 1)			
Regular	Stable	2xp1	p1
"	Unstable	2xp1	2xp1
Improved	Stable	1.5xp1	p1
"	Unstable	1.5xp1	1.5xp1
Extensive	Stable	p1	p1
"	Unstable	p1	p1
Improved Cover (IC = 2)			
Regular	Stable	2xp1	p2
"	Unstable	2xp1	2xp1
Improved	Stable	2xp2	p2
"	Unstable	2xp2	2xp2
Extensive	Stable	p2	p2
"	Unstable	p2	p2

The values p1 and p2 are functions of the alternative disposal sites considered, and are listed for each site in Table I.

The parameter f_c is given by the following:

$$f_c = M_o \, t_c \, \mathrm{MULT}(I6,I7,IS) \, 10^{(1-I9)} \qquad (4)$$

M_o is the dimensionless waste-stream-independent leachate/waste concentration partition ratio which is presented below for each of the radionuclides considered:

Nuclide	Ratio	Nuclide	Ratio	Nuclide	Ratio
H-3	1.15E+0	Tc-99	1.15E-1	Pu-239	4.67E-4
C-14	5.76E-3	I-129	1.15E-1	Pu-241	4.67E-4
Fe-55	1.48E-2	Cs-135	1.63E-4	Pu-242	4.67E-4
Co-60	1.48E-2	Cs-137	1.62E-4	Am-241	4.11E-3
Ni-59	1.48E-2	U-235	1.25E-4	Am-243	4.11E-3
Ni-63	1.48E-2	U-238	1.25E-4	Cm-243	4.67E-4
Sr-90	9.86E-3	Np-237	4.67E-4	Cm-244	4.67E-4
Nb-94	1.11E-2	Pu-238	4.67E-4		

M_o is estimated based upon experimental data from the Maxey Flats and West Valley disposal sites, at which several disposal cells exist which are under completely saturated conditions; it is determined as the ratio of the average concentration of the radionuclide in samples of leachate withdrawn from an innundated disposal cell to the average concentration of the radionuclide in the waste disposed in the disposal cells (ref. 6). All unsolidified waste streams are assigned the above leaching fractions.

Solidified waste streams, however, are assumed to leach at lower rates which are given by the product of M_o and the parameter MULT(I6,I7,IS), which is dimensionless and waste stream specific. The values of MULT are given by the following table:

Solidification Scenario	I6	MULT(I6,I7,IS) IS=2 or 3 and I7=0	 IS=0 or 1 or I7=1
Base	1	1	1
Cement	2	1/30	1/7.5
Syn. Pol.	3	1/160	1/40
Optimistic	4	1/400	1/100

Two alternative MULT lists are given depending upon waste form and disposal technology considerations. The first list of fractional multipliers is assigned to solidified waste streams which contain little or no chemical or chelating agents and are disposed segregated from those wastes that do contain such agents. The second list of fractional multipliers is assigned to solidified waste strams which do contain chemical or chelating agents or are disposed in the same disposal cells as waste which contain such agents.

The parameter $10^{(1-I9)}$ is a correction for waste streams, such as control rods, in which the radioactivity is bound up within an activated metal matrix. The value of this parameter is equal to unity in most cases.

The final factor, t_c, is the dimensionless waste-stream-specific leachate/waste contact time fraction. In reference 6, this factor was estimated to be a function of both the percolation rate and the speed with which the infiltrating percolation flows past the waste stream, i.e:

$$t_c = p/(nv) \qquad (5)$$

where p is the percolation discused above, n is the effective porosity of the backfill/waste stream mixture in the disposal cell, and v is the speed of the infiltrating precipitation in m/yr. In reference 6 and this paper, n was assumed to be equal to 0.25. The parameter v was assumed to be 1 ft/day for disposal of waste using a relatively nonpermeable backfill and 10 ft/day for disposal of waste using a permeable backfill (e.g., sand). Combining equations (2) through (5) yields:

$$J_o = C\ S\ p^2\ M_o\ \text{MULT(I6,I7,IS)}\ 10^{(1-I9)}/(nv) \qquad (6)$$

Several observations can be made:

(1) The source term is proportional to the square of the percolating precipitation. Consequently, one would expect a similar behavior in the calculated radiological doses. However, this is not totally the case, since the "source duration time" also affects the calculated doses. That is, given a fixed initial inventory of radionuclides which is annually releasing a portion of this initial inventory over time, the time required from the onset of leaching to the depletion of the inventory is termed the source duration time. A larger source term implies a smaller source duration time.

(2) The source term is linearly proportional to the contact time. If this factor were to be reduced through mitigative measures (e.g., adding sand as disposal cell backfill thereby increasing the speed of the percolating precipitation), a similar reduction in the radiological doses would be expected. However, as pointed out above, the source duration time also effects this proportionality.

(3) The source term is linearly proportional to the product of the radionuclide concentration in the waste stream, C, and the total ground surface area (S) of the fractional portion of the disposal facility containing the waste stream. The combined effect of these two parameters can be neglected since the decrease in waste concentration resulting from waste solidification is compensated for by the increase in the fractional surface area corresponding to the waste stream.

Migration Model Variations

The mathematical bases of the migration model and their interdependence with the environmental parameters can be found in references 6 and 7. Briefly, the factor r_{ik} for a given radionuclide i in waste stream k is given by the following equation:

$$r_{ik} = \sum_{j=1}^{J} [\exp(-\lambda_i t)/(J x T_k)]\ [F_j(t) - F_j(t-T_k)] \qquad (7)$$

where λ_i is the decay constant of the radionuclide; t is the time after disposal at which the migration reduction factor is applicable; J is the total number of longitudinal sectors the disposal site has been divided into, which is 10 in this work ; T_k is the source duration time for the k^{th} waste stream; and j denotes the disposal site sector considered. The function $F_j(t)$ is given by the following formula:

$$F_j(t) = 0.5\ U(t)\ [\mathrm{erfc}(X_-) + \exp(P_j)\ \mathrm{erfc}(X_+)] \qquad (8)$$

$$X_{\pm} = \frac{\sqrt{P_j}}{2}\ \frac{1 \pm t/(Rt_{wj})}{\sqrt{t/(Rt_{wj})}} \qquad (9)$$

where U(t) is the unit impulse function that is zero for a negative argument and is equal to unity otherwise; t_{wj} is the water travel time between the disposal sector being considered and the biota access location; P_j is the Peclet number for the distance between the disposal sector and the biota access location; R is the retardation coefficient of the radionuclide; and erfc(x) is the complement of the error function and is given by the formula:

$$\mathrm{erfc}(x) = 1 - \int_0^x (2/\sqrt{\pi})\ \exp(-t^2)\ dt \qquad (10)$$

The retardation coefficients R that are utilized in the above equations depend on the radionuclide as well as the geochemistry of the soils and the transporting groundwater. These coefficients are given in reference 5.

The source duration time T_k for the k^{th} waste stream is determined by dividing the total activity in the stream with the annual source term, i.e, J_{oik}. This calculation conservatively neglects the depletion of the radionuclide inventory at the disposal facility by previous releases or by radioactive decay.

TABLE I . Environmental Parameters for Regional Locations

Parameter	Symbol	North east	South east	Mid west	South west	Variation of SE
Travel Times - years						
Between Sectors	DTTM	400	64	120	8	16
Intruder Well	TTM(1)	200	42	130	280	10
Boundary Well	TTM(2)	350	66	175	283	18
Population Well	TTM(3)	2500	400	2100	580	100
Surface Water	TTM(4)	5000	800	3800	880	200
Peclet Numbers						
Between Sectors	DTPC	800	1600	800	800	1600
Intruder Well	TPC(1)	400	1300	400	1300	1300
Boundary Well	TPC(2)	700	1900	700	1600	1900
Population Well	TPC(3)	10000	10000	12500	30000	10000
Surface Water	TPC(4)	20000	20000	25000	60000	20000
Dilution Factors - m^3						
Intruder Well^a	QFC(1)	7700	7700	7700	7700	7700
Boundary Well^a	QFC(2)	7700	7700	7700	7700	7700
Population Well	QFC(3)	2.0E+5	2.0E+5	2.0E+5	2.0E+5	2.0E+5
Surface Water	QFC(4)	4.5E+6	4.5E+6	4.5E+6	b	4.5E+6
Percolation - mm						
Percolation 1	p1	74	180	50	1	180
Percolation 2	p2	37	30	25	1	30
Retardation Coefficient Set Used	NRET	4	3	3	2	2

(a) Dilution volumes at the intruder and boundary wells are determined by the relationship TVOL = 352,000 x p1, where 352,000 is the approximate area (in square meters) of the disposal area. The value 7700 represents the minimum practical dilution volume (in cubic meters) and is substituted in the computer codes for TVOL if TVOL is less than 7700.

(b) Surface water impacts are not applicable for this site.

The groundwater travel times, t_{wi}, depend on the distance between the disposal facility sector being considered and the biota access location, and the groundwater velocity. The travel time between the first sector and the biota access location is denoted by t_{w1}. The assumed values of t_{wi} for the five disposal facility sites are presented in Table I.

The Peclet number, P_i, is the groundwater travel distance from the disposal facility sector to the biota access location divided by the longitudinal dispersivity of the medium. Peclet numbers for the distances between the sectors are determined in a manner similar to the travel times. The assumed values of P_i for the five disposal facility sites are presented in Table I.

Qualitative Behavior of Migration

One aspect of the migration model requires further clarification. This is the qualitative behavior of the radionuclide source terms during groundwater migration. Consider a point source of radioactivity releasing this activity into the groundwater over a source duration time period, T. The shape of the source term at a time slightly greater than T can be approximated by Figure 1(a). As this block of radioactivity moves downstream of the source location, the dispersion of the contaminants in the soil medium reshapes the activity as shown in Figure 1(b). The shapes are functions of the Peclet numbers.

Higher source terms can occur through a multitude of reasons including higher percolation rates into the disposal cells (which may be due to site environmental characteristics or disposal technology characteristics), or higher leaching rates of waste forms, or not segregating waste streams containing chelating agents or organic chemicals. The effect of a case in which the retardation coefficients and/or the groundwater travel times (which are inversely proportional to the speed of the groundwater traveling through the medium) are higher can be represented by Figures 2(a) and 2(b). This is because these two parameters appear as a product in the equations, consequently their effect is similar.

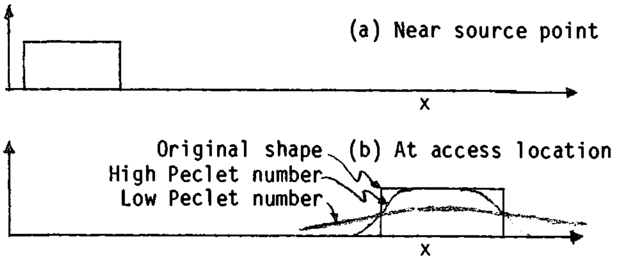

Fig. 1. Point Source Case 1

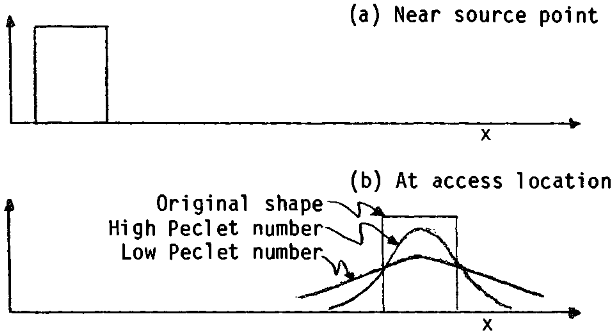

Fig. 2. Point Source Case 2

When there are multiple point sources, as is the case in this paper, each point source can be plotted separately and the envelope of the concentrations resulting from these sources considered. In this paper, the disposal facility has been divided into 10 sectors, and 10 point sources are considered simultaneously. For purposes of illustration, the combined effect of only four point sources are considered below.

When the magnitude of the source term is small and/or the retardation coefficients are small and/or the groundwater travel times are small (higher groundwater speeds), the concentration peaks from the individual sources overlap significantly near the source points. This is illustrated in Figure 3(a). Downstream of the source point, a smooth concentration profile that lasts a considerable time is observed, as illustrated in Figure 3(b).

When the reverse is the case, the concentration peaks remain distinct near the source points; this is illustrated in Figure 4 (a&b).

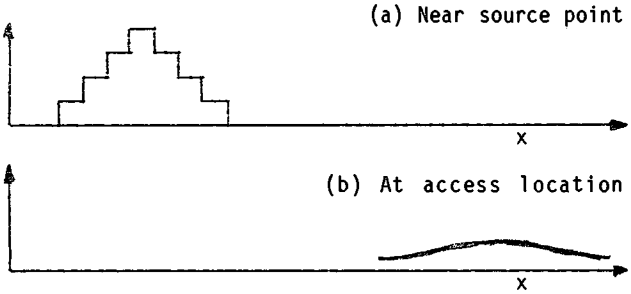

Fig. 3. Multiple Source Case 1

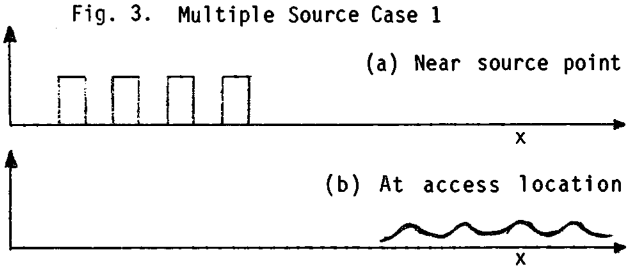

Fig. 4. Multiple Source Case 2

A corresponding effect is observed downstream of the sources. The peaks may blend into one smooth peak or, depending on the Peclet number, they may remain separated.

RESULTS

The results of the sensitivity analysis are voluminous and are provided in reference 5. Briefly, however, the analysis was performed in two phases. The first phase calculated potential exposures in terms of dose rate to an individual (mrem/yr) at several time periods following disposal site closure. Dose rates were calculated for two organs (whole body and thyroid) at two biota access locations: a well located at the site boundary and used by an individual (boundary well), and a well located farther down gradient from the site and used by a small population (population well). In this first phase, 48 separate disposal technology cases were considered for each of the five disposal sites. For each of the resulting 240 cases, 4 solidification scenarios for the waste streams suitable for solidification are considered.

For the second phase, a few cases were considered in more detail. These cases involved the step by step addition of additional disposal technologies at a single disposal site, which resulted in successive reductions in the annual quantities of rainwater percolating into the disposal cells. The disposal technology indices for five of these cases are given below:

Case	Description	Index Values IC	IX	IE	IS
201	Worst Case	1	1	1	0
207	Permeable Backfill plus Chemical Segregation	1	1	4	2
208	Case 7 plus Unstable/ Stable Segregation	1	1	4	3
239	Case 7 plus Improved Cover and Compaction	2	2	4	2
240	Case 39 plus Unstable/ Stable Segregation	2	2	4	3

In addition to dose rates, cumulative exposures were calculated at the biota access locations over a given time period. A comparison was also made between the costs for implementing improved disposal technologies and the costs for implementing improved solidification scenarios.

Some of the results of the analysis for the southeast disposal site (IR = 2) are given below. Table II gives dose rates to the thyroid at four times after facility closure for the above five cases and three solidification scenarios. Table III gives cumulative whole body doses as calculated at various times after facility closure.

TABLE II . Annual Dose Rates (mrem/year)

Case	Perc[a]	Time[b]	Thyroid Dose Rates (mrem/yr) Base	Cement	Opt.
201	360	120	9.76E+0	9.74E+0	9.73E+0
	360	1000	5.86E+2	1.26E+2	6.07E+1
		5,000	1.17E+3	2.52E+2	1.22E+2
		10,000	2.62E+1	1.68E+2	3.67E+1
207	360	120	9.75E-1	9.74E-1	9.74E-1
	360	1000	4.68E+1	5.85E+0	4.54E+0
		5,000	1.17E+2	1.46E+1	1.14E+1
		10,000	1.17E+2	1.46E+1	1.14E+1
208	360	120	2.47E-1	2.47E-1	2.47E-1
	180	1000	1.43E+1	4.10E+0	3.77E+0
		5,000	3.59E+1	1.03E+1	9.44E+0
		10,000	3.59E+1	1.03E+1	9.43E+0
239	60	120	2.72E-2	2.72E-2	2.72E-2
	60	1000	1.31E+0	1.63E-1	1.27E-1
		5,000	3.27E+0	4.09E-1	3.17E-1
		10,000	3.27E+0	4.08E-1	3.17E-1
240	60	120	6.90E-3	6.89E-3	6.89E-3
	30	1000	4.01E-1	1.14E-1	1.05E-1
		5,000	1.00E+0	2.87E-1	2.64E-1
		10,000	1.00E+0	2.86E-1	2.63E-1

(a) Percolation in mm/yr. The first value is for percolation into disposal cells containing unstable waste streams, the second value is for percolation into disposal cells containing stable waste streams.

(b) Time in years after disposal facility closure at which dose rates are calculated.

TABLE III. Cumulative Doses (mrem)

			Whole Body Cumulative Doses (mrem)		
Case	Perc[a]	Time[b]	Base	Cement	Opt.
201	360	120	3.56E+3	3.56E+3	3.56E+3
	360	1000	4.23E+3	3.90E+3	3.85E+3
		10,000	1.89E+4	1.00E+4	8.26E+3
207	360	120	3.56E+2	3.56E+2	3.56E+2
	360	1000	4.10E+2	3.85E+2	3.84E+2
		10,000	2.24E+3	8.83E+2	8.40E+2
208	360	120	9.03E+1	9.01E+1	9.01E+1
	180	1000	1.08E+2	1.01E+2	1.01E+2
		10,000	8.67E+2	5.29E+2	5.19E+2
239	60	120	9.95E+0	9.93E+0	9.93E+0
	60	1000	1.15E+1	1.07E+1	1.07E+1
		10,000	6.24E+1	2.47E+1	2.35E+1
240	60	120	2.52E+0	2.52E+0	2.52E+0
	30	1000	3.01E+0	2.83E+0	2.82E+0
		10,000	2.42E+1	1.48E+1	1.45E+1

(a) Percolation in mm/yr. The first value is for percolation into disposal cells containing unstable waste streams, the second value is for percolation into disposal cells containing stable waste streams.

(b) Cumulative doses as calculated up to the time indicated (in years).

CONCLUSIONS

Based upon the analysis, a number of conclusions can be reached. These include:

(1) Reducing the leaching potential of the radionuclides contained in the few waste streams which are suitable for solidification helps to reduce calculated radiological exposures due to groundwater migration. However, the relative effectiveness of improved solidification to reduce exposures rapidly decreases from one solidification scenario to the next.

The relationship between the reduction of the leaching potential of the waste streams suitable for solidification and the reduction of the calculated exposures appears to be approximately asymptotic rather than linear. As the leaching potential of the waste streams suitable for solidification is reduced, a point is rapidly reached in which further reductions in the leaching potential have little effect on the calculated impacts. This is because only a limited volume (about 25%) of the total waste disposed is actually suitable for solidification, and even if the releases from the waste streams suitable for solidification were reduced to zero, there would still be the releases from all the waste streams which are not suitable for solidification.

(2) In comparison with other factors such as percolation and contact time, improving the leaching potential of the waste streams suitable for solidification appears to have a less significant influence on calculated exposures. Consequently, factors such as waste structural stability, segregation, or improved backfill which contribute to the reduction of percolation and contact time appear to be more important than the leaching potential of such waste streams.

(3) The establishment of an extremely rigorous leach rate criteria within the framework of the 10 CFR Part 61 requirements does not appear to be necessary to assure safe near-surface disposal of radioactive waste. Consequently, waste form improvements that can be conventionally achieved with solidification products such as cement, bitumen, vinyl ester styrene, or synthetic polymers appear to be acceptable provided that the final product results in a structurally stable waste form.

The analysis indicates that reduced leaching of solidified waste streams is useful in reducing calculated exposures, implying that some manner of minimum solidified waste leaching standard may be useful. However, the analysis also indicates that there is little to be gained by setting an extremely rigorous standard. The standard would really only need to exclude extremely poor quality solidification binders from use. A more important standard may be one which relates to the structural stability of the solidified waste form, since experimental evidence has indicated that binders exhibiting poor structural stability have tended to also exhibit poor leaching performance.

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