A PRELIMINARY PERFORMANCE ASSESSMENT FOR NEAR-SURFACE LAND DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTES

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1. INTRODUCTION

This paper discusses a preliminary performance assessment of facilities for near-surface land disposal of low-level radioactive wastes. The analysis assumes environmental conditions representative of the Oak Ridge Reservation (ORR). However, the assessment is not intended to provide realistic predictions of the performance of currently operating disposal facilities on the ORR or facilities that will be developed in the future, because the analysis is largely generic and involves many presumably conservative assumptions that often are used in the absence of data for specific sites and facilities and validated models of system performance. Rather, the assessment is intended primarily as a screening tool in planning for new disposal facilities on the ORR and in identifying important radionuclides for which a more realistic analysis is needed.

The Department of Energy (DOE) Order 5820.2A [1] has established performance objectives for low-level waste disposal that will apply to new facilities on the ORR. These performance objectives include limits on annual effective dose equivalent of 25 mrem for members of the public beyond the boundary of the disposal site and 100 mrem for continuous exposures of inadvertent intruders onto the disposal site following loss of active institutional control, which is assumed to occur at 100 years after facility closure. In this paper, dose estimates for off-site individuals and inadvertent intruders are compared with the performance objectives to identify the principal radionuclides of concern.

Two types of waste disposal facilities are assumed: shallow trenches or above-grade tumuli. However, no credit is taken in the analysis for the waste-isolation capabilities of engineered disposal facilities and waste forms following loss of active institutional control. The analysis for the two types of facilities differs only in the model assumed for transport of radionuclides by water pathways. For trench disposal, radionuclides are transported to an underlying aquifer by infiltrating precipitation; for tumulus disposal, radionuclides are transported to nearby surface water by overland runoff.

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2. RADIONUCLIDE COMPOSITION OF WASTES

Table 1 presents the assumed generation rates of radionuclides requiring disposal. These estimates are based on disposal records for the ORR over the last decade. For those radionuclides generated at more than one site on the ORR, separate estimates for each site are given. We particularly note that the generation rate of unidentified activity is nearly as large as the combined generation rates of the important fission products Sr-90 and Cs-137. The potential impacts of such large quantities of unidentified activity on the dose estimates for off-site individuals and inadvertent intruders are considered in this analysis. Estimates of current inventories of stored Tc-99 and isotopes of uranium at two sites on the ORR are given in Table 2, and Table 3 gives the estimated volumes of generated and inventoried wastes at the three sites.

Estimates of average radionuclide concentrations in the wastes prior to disposal are obtained from the data in Tables 1-3. For Tc-99 and isotopes of uranium, which are both generated and stored, the average concentrations in all wastes are based on the assumption that the operating lifetime of the disposal facility is 10 years. In estimating average radionuclide concentrations after disposal, the concentrations prior to disposal are reduced by a factor of four to account for mixing of the wastes with soil and the presence of void spaces [2]. The resulting estimates of radionuclide concentrations in the disposal facility at the time of facility closure, which ignore radioactive decay during the operating lifetime of the facility, are given in Table 4.

3. RADIONUCLIDE CONCENTRATIONS IN WATER IN DISPOSAL FACILITY

Mobilization and release of radionuclides from the disposal facility is assumed to result from infiltration of precipitation and leaching of the radionuclides from solid waste into solution. Estimates of the concentrations of radionuclides in water in the disposal facility are based on the following assumptions:

- No water enters the disposal facility during the period of active institutional control.
- All barriers to infiltration of precipitation fail completely upon loss of active institutional control, which occurs at 100 years after facility closure [1].
- All radionuclides in the waste are completely immersed in water at the time of facility failure.
- Most radionuclides are completely soluble in water, and the resulting concentration in water is obtained directly from the concentration in the waste. For selected radionuclides, the concentration in water is based on the solubility limit given in Table 5.

The assumptions regarding facility failure presumably are unreasonably conservative for engineered facilities and waste forms that will be used

for future disposals on the ORR. However, even if all barriers to contact of waste by water were to fail completely at 100 years after closure, the model described above probably results in considerable overestimates of the concentrations in water that would occur for some radionuclides. For example, for radionuclides in activated metal (e.g., Be-10 and isotopes of europium), it is highly unlikely that all activity would be immersed in water and go into solution immediately following facility failure. In addition, application of the solubility limits in Table 5 to Be-10, Zr-93, and Sn-121m does not take into account the appreciable (but unknown) concentrations of stable isotopes of these elements.

Table 6 gives the estimated concentrations of radionuclides in the solid waste at the time of facility failure, as obtained from the results in Table 4 corrected for radioactive decay during the 100-year period of active institutional control, and the estimated concentrations in the leachate in the disposal facility obtained from the assumptions described above. The unidentified activity is assumed to be a mixture of Sr-90 and Cs-137 in the same proportions as the estimated generation rates of these isotopes in Table 1 and, thus, to have a half-life of about 30 years. This assumption probably results in overestimates of the concentrations of unidentified activity at the time of facility failure, because this activity presumably contains substantial quantities of shorter-lived isotopes. Results for short-lived radionuclides in Table 4 that decay to innocuous levels within 100 years are omitted from Table 6.

Two additional points concerning the results in Table 6 should be noted. First, for Tc-99 and isotopes of uranium, the concentrations arising from operations at the three sites on the ORR are reported separately and are not combined to obtain an average concentration for all wastes. Such a separation can be useful in planning for waste management at the different sites. Second, in estimating the concentrations in solution for isotopes of uranium and plutonium on the basis of the solubility limits in Table 5, the amount of each isotope in solution must be apportioned by mass in the solid waste rather than by activity.

4. ENVIRONMENTAL TRANSPORT VIA WATER PATHWAYS

This section describes the estimates of radionuclide concentrations in ground water for disposal of wastes in shallow trenches and in surface water for disposal in above-grade tumuli.

4.1 Trench Disposal

For disposal in shallow trenches, the waste leachate is assumed to infiltrate downward through a layer of unsaturated soil to an underlying aquifer which is used as a water supply for off-site individuals and inadvertent intruders. The assumptions used in estimating the maximum concentrations of radionuclides in the aquifer are summarized as follows:

- The waste leachate generated in the disposal facility enters the soil below the trenches essentially immediately upon facility failure.

- The waste leachate infiltrates through the unsaturated soil at an average rate of 1.4 m per year to an aquifer located an average distance of 15 m below the trenches [2].

- Half of the infiltrating precipitation passes through the waste trenches and becomes contaminated. As a result, radionuclides that are not retarded and do not decay appreciably during transport through the unsaturated soil have maximum concentrations in the aquifer that are one-half the concentrations in the waste leachate in the disposal facility given in Table 6.

- Radionuclide transport in the unsaturated soil is subject to retardation, which is proportional to the equilibrium distribution coefficient Kd.

- Waste leachate that reaches the underlying aquifer is not diluted further within the aquifer, and retardation of radionuclides during transport in the aquifer is not considered. As a result, the concentration of radionuclides in water drawn from a well by off-site individuals or inadvertent intruders does not depend on an assumed location for the well.

In estimating the effects of radionuclide retardation during transport in unsaturated soil on the concentrations in the aquifer, the radionuclides are divided into six groups according to their assumed values of Kd. The assignment of radionuclides to these groups and the associated Kd values are given in Table 7. The Kd values for each group are obtained from ref. [2], and the group assignments for Be, Co, Ni, Sn, Sm, Eu, Th, Np, Pu, and Am are based on data given in Fig. 2.31 of ref. [3]. Uranium is assigned to Group 2 when the concentration in the solid waste exceeds the solubility limit in Table 5. This assignment is based on the observation of a strongly decreasing Kd with increasing solution concentration for uranium sorption in soil from the ORR [4].

For each group of radionuclides, Table 7 also gives estimates of the maximum concentration in the aquifer relative to the concentration in the trench leachate, assuming no radioactive decay during transport, and the time after facility failure at which the maximum concentration occurs. These results are based on the assumptions described above and model calculations summarized in Figs. 5 and 6 of ref. [2].

Two aspects of the model for transport of radionuclides from shallow trenches are questionable. First, downward infiltration of waste leachate in the unsaturated zone may occur in preferential flow paths, rather than a homogeneous porous medium, at a rate considerably greater than the assumed value. Second, the assumed effects of retardation may not properly describe radionuclide transport in unsaturated soil.

4.2 Tumulus Disposal

For disposal in above-grade tumuli, the waste leachate is assumed to be transported to nearby surface water by overland runoff essentially

immediately upon facility failure. Further, we assume no dilution of the leachate during overland transport and no loss of contaminants due to infiltration of water into soil or sorption of radionuclides onto soil particles. The latter two assumptions probably are conservative for above-grade disposal on the ORR.

With these assumptions, the radionuclide concentrations in surface water relative to the concentrations in the waste leachate are given by the ratio of the flow rate of water from the tumuli to the flow rate of surface water. For this analysis, we assume a dilution factor of 110 in estimating radionuclide concentrations in surface water. This assumption is based on average overland flow rates for portions of the ORR [5] and our estimate of the minimum flow rate of surface water that is sufficient to provide a continuous water supply for individuals. Thus, a radionuclide concentration in surface water is obtained by dividing the corresponding solution concentration in Table 6 by this dilution factor. No further dilution during transport in surface water to locations accessed by off-site individuals or inadvertent intruders is assumed. This model presumably overestimates radionuclide concentrations in surface water relative to the solute concentrations in the disposal facility. As opposed to the case of trench disposal, the maximum concentration of all radionuclides in surface water occurs at the same time, i.e., essentially at the time of facility failure.

5. DOSE ANALYSIS FOR WATER PATHWAYS

The dose analysis for radionuclides transported from the disposal facility by water pathways is the same for off-site individuals and inadvertent intruders. The assumed exposure pathways include ingestion of contaminated drinking water, either from ground water for trench disposal or from surface water for tumulus disposal, and ingestion of milk and meat from dairy and beef cattle that drink contaminated water from the same sources. Use of contaminated water to irrigate food crops consumed by the individuals is neglected, because rainfall is usually abundant on the ORR and irrigation is not commonly practiced. The annual effective dose equivalents per unit concentration of radionuclides in water for the drinking water, milk, and meat pathways combined were calculated as described in Appendix A of ref [6]. For most radionuclides, the drinking water pathway is by far the most important [6].

The results of the dose analysis for the water pathways for trench and tumulus disposal are given in Tables 8 and 9, respectively. Each table gives the maximum concentrations in water estimated as described in Sections 3 and 4 (for trench disposal, radioactive decay during transport to the underlying aquifer is also taken into account), the factors for converting radionuclide concentrations in water to annual effective dose equivalents obtained from Table A-20 of ref. [6], and the estimated maximum annual effective dose equivalents.

The results in Table 8 for trench disposal indicate that only a few radionuclides would reach the aquifer in concentrations sufficient to give estimated annual effective dose equivalents greater than 1 mrem. The very

small estimated doses for the other radionuclides result from such factors as the half-life and assumed concentration in the solid waste, retardation factor during transport to the aquifer, or solubility limit. The unimportance of the unidentified activity results from the assumption that this activity is a mixture of Sr-90 and Cs-137. Again, however, we caution that the model for infiltration of waste leachate and radionuclide retardation in the unsaturated zone described in Section 4.1 could be inappropriate.

For trench disposal, we again note that the maximum concentrations in the aquifer for H-3, C-14, Tc-99, and isotopes of uranium do not all occur at the same time (see Table 7). Thus, the total dose would not be the sum of the doses from each radionuclide. The estimated annual dose in Table 8 for Tc-99 from the K-25 site exceeds the performance objectives of 25 mrem for off-site individuals and 100 mrem for inadvertent intruders [1], and the estimated annual doses for isotopes of uranium from each of the X-10, K-25, and Y-12 sites exceed the performance objective for off-site individuals. The total dose from uranium would not be the sum of the contributions from the isotopes generated at each site because a solubility limit was applied to this element (see Table 5). For all other radionuclides, the annual dose for the ground water pathway from trench disposal is less than either performance objective.

For tumulus disposal, the total dose would be the sum of the doses from all radionuclides, because no retardation was assumed during transport from the disposal facility to surface water. The estimated annual doses in Table 9 for Sr-90, Cs-137, and Am-241 exceed the performance objectives for off-site individuals and inadvertent intruders, and the estimated annual doses for Tc-99 from the K-25 site, Eu-152, and Cm-244 exceed the performance objective for off-site individuals. As in the case of trench disposal, the total dose from uranium would not be the sum of the contributions from the isotopes generated at the three sites.

Again, the dose estimate for the unidentified activity in Table 9 is based on the assumption that this activity is a mixture of Sr-90 and Cs-137. The high maximum annual dose in comparison with the performance objectives for off-site individuals and inadvertent intruders indicates the potential importance of the unidentified activity in evaluating compliance of the disposal facility with the performance objectives.

6. DOSE ANALYSIS FOR INTRUSION INTO SOLID WASTES

The dose analysis for inadvertent intruders into the disposal facility following loss of active institutional control is the same for shallow trenches and above-grade tumuli. Intrusion is assumed to occur at 100 years after disposal, at which time all wastes are assumed to be in solid form and indistinguishable from native soil. Exposures of inadvertent intruders to the solid wastes are assumed to occur according to an intruder-homesteader scenario. In this scenario, the following exposure pathways are assumed:

- ingestion of vegetables grown in soil contaminated by mixing of wastes with uncontaminated soil on the disposal site;

- ingestion of contaminated soil from the vegetable garden in conjunction with vegetable intakes;

- external exposure to contaminated soil during indoor residence on the site and while working in the vegetable garden; and

- inhalation of suspended activity from contaminated soil during indoor residence on the site and while working in the vegetable garden.

The annual effective dose equivalents per unit concentration of radionuclides in the disposal facility for all pathways combined were calculated as described in Appendix A of ref. [6].

The results of the dose analysis for direct intrusion for both trench and tumulus disposal are given in Table 10. The radionuclide concentrations in the solid waste at the time intrusion occurs were obtained from Table 6, and the factors for converting radionuclide concentrations to annual effective dose equivalents were obtained from Table A-21 of ref. [6]. The estimated annual effective dose equivalents exceed the performance objective of 100 mrem [1] for Sr-90, Tc-99 from the K-25 site, Cs-137, Eu-152, Th-232, and U-235 from the X-10 site. The dose estimate for Be-10 is the same as the performance objective, and the estimate for U-238 from the X-10 site is nearly the same. Finally, the dose estimate for the unidentified activity far exceeds the performance objective if this activity is assumed to be a mixture of Sr-90 and Cs-137. The total dose would be the sum of the estimated doses from all radionuclides.

7. SUMMARY

This paper has presented a preliminary performance assessment of facilities for near-surface land disposal of radioactive wastes. The assessment is not intended to provide realistic predictions of the performance of disposal systems. Rather, the analysis involves a number of generic and presumably conservative assumptions which are used in the absence of data and validated models for specific sites and disposal facilities, and the analysis investigates the effect of these assumptions on the acceptability of low-level waste disposal on the ORR according to the performance objectives established in DOE Order 5820.2A [1].

For transport of radionuclides by water pathways, the most important assumptions that likely result in overestimates of doses to off-site individuals and inadvertent intruders are summarized as follows:

- All radionuclides are solubilized in water immediately upon loss of institutional control over the disposal facility at 100 years after disposal. For all radionuclides except those listed in Table 5, the concentration in solution thus is determined by the concentration in solid waste regardless of its physical and chemical form.

- For disposal in shallow trenches, radionuclide retardation is taken into account only during transport of waste leachate from the disposal facility through unsaturated soil to an underlying aquifer but not during transport in the aquifer to a well used by off-site individuals or inadvertent intruders.

- The dilution factor for transport of radionuclides from shallow trenches to an underlying aquifer is only a factor of two, and no further dilution during transport in the aquifer is considered.

- For disposal in above-grade tumuli, transport of waste leachate by overland runoff to nearby surface water essentially occurs instantaneously and without infiltration into soil or retardation due to sorption of radionuclides onto soil particles.

We have also emphasized, however, that the model for infiltration of waste leachate to the underlying aquifer and radionuclide retardation in transport through unsaturated soil may not be appropriate.

For exposure of inadvertent intruders into the disposal facility following loss of institutional control, the most important assumptions that likely result in overestimates of dose are summarized as follows:

- Intrusion into the solid wastes occurs immediately upon loss of institutional control.

- At the time of intrusion, all wastes in the disposal facility are indistinguishable from native soil regardless of their physical form at disposal, and an intruder-homesteader exposure scenario occurs with a probability of unity.

In essence, the assumptions in the dose analysis do not take into account any long-term waste isolation capabilities of engineered disposal systems or waste forms as they would affect transport of radionuclides by water pathways or exposure of inadvertent intruders to the solid wastes.

Comparison of the dose estimates with the DOE's performance objectives indicates that only a few of the many radionuclides in wastes generated on the ORR are of concern. The important radionuclides in the dose analysis are summarized as follows:

- for exposures of off-site individuals and inadvertent intruders by the ground water pathway from disposal in shallow trenches: Tc-99 and isotopes of uranium;

- for exposures of off-site individuals and inadvertent intruders by the surface water pathway from disposal in above-grade tumuli: Sr-90, Tc-99, Cs-137, Eu-152, Am-241, and Cm-244; and

- for exposure of inadvertent intruders from direct intrusion into shallow trenches or above-grade tumuli: Be-10, Sr-90, Tc-99, Cs-137, Eu-152, Th-232, and isotopes of uranium.

In addition, the analysis shows that unidentified activity in the waste is potentially of great importance. By assuming that this activity is a mixture of Sr-90 and Cs-137, which probably results in overestimates of potential doses from these materials, the doses from the surface water pathway for tumulus disposal and from direct intrusion into the solid wastes far exceed the applicable performance objectives. Therefore, it is clearly important to reduce the amount of unidentified activity in characterizing waste streams on the ORR.

8. CONCLUSIONS

Although the dose analysis in this paper involves many unrealistic and presumably conservative assumptions, it should be emphasized that the degree of overestimation of doses to off-site individuals or inadvertent intruders probably depends on the particular radionuclide. For example, it is likely that the estimated dose from Eu-152, either for the surface water pathway for tumulus disposal or as a result of direct intrusion into solid waste, is much greater than doses that actually would be received, because this radionuclide occurs in activated metal which is relatively insoluble [2] and the waste probably would not be accessible to an intruder according to the assumptions for the intruder-homesteader scenario until the activity has decayed to innocuous levels. That is, the particular physical form in which this isotope occurs in conjunction with its half-life renders the dose estimates highly unlikely. We also believe that the estimated dose to inadvertent intruders from Be-10 is unreasonably high, partly because this isotope also occurs in a relatively insoluble activated metal [2] and partly because the reported inventory (400 Ci in a single disposal) seems unrealistic. It also seems unlikely that Cm-244 would be of concern in a more realistic dose analysis for tumulus disposal due to its relatively short half-life.

On the other hand, Th-232 is very long-lived and expected to be quite immobile in the environment [2]. Thus, the dose estimate for inadvertent intruders based on the assumed homesteader scenario may be reasonable at times far into the future even if the performance of engineered disposal facilities and waste forms were taken into account, because the engineered barriers probably would degrade well before the activity has decayed significantly. Similar considerations could apply to long-lived isotopes of uranium if a substantial fraction of these materials were immobile.

We also emphasize that the type of analysis presented in this paper, even though probably unrealistically conservative for many radionuclides, provides a useful screening tool in planning for disposal facilities and in identifying radionuclides of importance to a more realistic performance assessment. For example, it is probably reasonable to assume that doses to inadvertent intruders and off-site individuals can be prevented for the first 100 years after disposal by use of active institutional control, collection of any waste leachate, and environmental monitoring near the disposal facility. Therefore, most radionuclides for which the doses were found to be very small in this analysis (e.g., less than 1 mrem per year) probably can be neglected in a more realistic performance assessment, provided the estimated concentrations of these radionuclides in the wastes

are representative of actual waste compositions. A realistic performance assessment then can focus on a relatively few radionuclides.

We believe that the principal radionuclides of concern to low-level waste disposal on the ORR include Sr-90, Tc-99, Cs-137, and isotopes of uranium, and that Eu-152, Th-232, and Am-241 also warrant attention in a more realistic performance assessment. Site-specific data on long-term performance of engineered disposal systems and waste forms clearly will be important for many of these radionuclides. This is particularly the case for such radionuclides as Sr-90, Cs-137, and Eu-152 which have relatively short half-lives and for which engineered disposal systems and waste forms could be very effective in reducing doses to off-site individuals and in limiting the types of exposure scenarios and resulting doses that could occur for inadvertent intruders. A more realistic treatment of mobilization and transport of radionuclides via water pathways also is needed. Such an analysis could significantly reduce estimated doses for some of the important radionuclides but could increase estimated doses for other waste constituents. Finally, consideration of the long-term stability of the geologic environment is needed. Changes in the geologic environment over time could increase the potential for mobilization and transport of such important long-lived radionuclides as Th-232 and isotopes of uranium.

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Table 1. Estimated generation rates of radionuclides for disposal in low-level waste facility[a]

Nuclide	Half-life (y)	Curies per year	Nuclide	Half-life (y)	Curies per year
H-3	12.28	8.4E2	Eu-155	4.96	3.4E3
Be-10	1.6E6	4.4E1	Th-232	1.405E10	3.4E-1
C-14	5730	2.7E1	U-233	1.592E5	2.5E1
Na-22	2.602	1E-2	U-234	2.445E5	4.8E-1[b]
Fe-55	2.7	1E-1			2.9[c]
Co-60	5.271	4.3E3	U-235	7.038E8	1.1E1
Ni-63	100.1	1E-4			3.0E-2[b]
Sr-90	28.6	3.3E2			1.4E-1[c]
Zr-93	1.53E6	1.8	U-238	4.468E9	2.2E1
Tc-99	2.13E5	4.1			1.2E-1[b]
		6.1E1[b]			2.1[c]
Ru-106	1.01	1E2	Np-237	2.14E6	1E-4
Cd-113m	13.7	1E-4	Pu-238	87.75	1E-3
Sn-121m	55	1.1	Pu-239	24131	1.3E-2
Cs-134	2.062	8.6	Am-241	432.2	3E-1
Cs-137	30.17	5.6E2	Am-243	7.38E3	2E-5
Pm-147	2.6234	1E1	Cm-242	0.447	1E-1
Sm-151	90	6.3	Cm-244	18.11	2.7
Eu-152	13.6	5.7E3	Bk-249	0.88	1E-5
Eu-154	8.8	8.1E3	Cf-252	2.639	1E-3
			UNID[d]	-	8.1E2

[a]Values are for wastes generated at X-10 site, except as noted.

[b]Value for wastes generated at K-25 site based on operations prior to placing plant in standby mode.

[c]Value for wastes generated at Y-12 site.

[d]Denotes unidentified activity.

Table 2. Estimated stored inventories of radionuclides for disposal in low-level waste facility

Nuclide	Site	Curies
Tc-99	K-25	4.3E2
U-234	K-25	1.1
	Y-12	5.4E1
U-235	K-25	6.0E-2
	Y-12	2.5
U-238	K-25	8.0E-1
	Y-12	5.2E1

Table 3. Estimated volumes of generated and inventoried wastes for disposal in low-level waste facility

Site	Generation rate (m^3 per year)	Inventory (m^3)
X-10	2.4E3	-
K-25	1.1E3[a]	2.2E4
Y-12	1.5E4	1.5E4

[a]Based on operations prior to placing plant in standby mode.

Table 4. Estimated average concentrations of radionuclides in disposal facility at time of facility closure[a]

Nuclide	Half-life (y)	$\mu Ci/m^3$	Nuclide	Half-life (y)	$\mu Ci/m^3$
H-3	12.28	8.8E4	Eu-155	4.96	3.5E5
Be-10	1.6E6	4.6E3	Th-232	1.405E10	3.5E1
C-14	5730	2.8E3	U-233	1.592E5	2.6E3
Na-22	2.602	1.0	U-234	2.445E5	4.5E1[b]
Fe-55	2.7	1.0E1			1.2E2[c]
Co-60	5.271	4.5E5	U-235	7.038E8	1.1E3
Ni-63	100.1	1.0E-2			2.7[b]
Sr-90	28.6	3.4E4			5.7[c]
Zr-93	1.53E6	1.9E2	U-238	4.468E9	2.3E3
Tc-99	2.13E5	4.3E2			1.5E1[b]
		7.9E3[b]			1.1E2[c]
Ru-106	1.01	1.0E4	Np-237	2.14E6	1.0E-2
Cd-113m	13.7	1.0E-2	Pu-238	87.75	1.0E-1
Sn-121m	55	1.1E2	Pu-239	24131	1.4
Cs-134	2.062	9.0E2	Am-241	432.2	3.1E1
Cs-137	30.17	5.8E4	Am-243	7.38E3	2.1E-3
Pm-147	2.6234	1.0E3	Cm-242	0.447	1.0E1
Sm-151	90	6.6E2	Cm-244	18.11	2.8E2
Eu-152	13.6	5.9E5	Bk-249	0.88	1.0E-3
Eu-154	8.8	8.4E5	Cf-252	2.639	1.0E-1
			UNID[d]	-	8.4E4

[a]Values are for wastes from X-10 site, except as noted.

[b]Value for wastes from K-25 site.

[c]Value for wastes from Y-12 site.

[d]Denotes unidentified activity.

Table 5. Assumed limits on solubility of elements in water[a]

Element	Solubility (mol/L)
Beryllium	6E-10
Zirconium	7E-12
Tin	2E-14
Thorium	8E-15
Uranium	4.5E-5
Plutonium	1E-12

[a]Values obtained from Table A.2 of ref. [2].

Table 6. Estimated average concentrations of radionuclides in solid waste and solution at time of facility failure[a]

Nuclide	Half-life (y)	Solid (μCi/m^3)	Solution (μCi/L)
H-3	12.28	3.1E2	3.1E-1
Be-10	1.6E6	4.6E3	1.3E-4[b]
C-14	5730	2.8E3	2.8
Co-60	5.271	8.7E-1	8.7E-4
Ni-63	100.1	5.0E-3	5.0E-6
Sr-90	28.6	3.0E3	3.0
Zr-93	1.53E6	1.9E2	1.6E-8[b]
Tc-99	2.13E5	4.3E2	4.3E-1
		7.9E3[c]	7.9[c]
Sn-121m	55	3.2E1	1.3E-4[b]
Cs-137	30.17	5.9E3	5.9
Sm-151	90	3.0E2	3.0E-1
Eu-152	13.6	3.6E3	3.6
Eu-154	8.8	3.2E2	3.2E-1
Eu-155	4.96	3.0E-1	3.0E-4
Th-232	1.405E10	3.5E1	2.1E-13[b]
U-233	1.592E5	2.6E3	4.0E-3[b]
U-234	2.445E5	4.5E1[c]	1.1E-2[b,c]
		1.2E2[d]	4.1E-3[b,d]
U-235	7.038E8	1.1E3	1.7E-3[b]
		2.7[c]	6.6E-4[b,c]
		5.7[d]	1.9E-4[b,d]
U-238	4.468E9	2.3E3	3.4E-3[b]
		1.5E1[c]	3.7E-3[b,c]
		1.1E2[d]	3.7E-3[b,d]
Np-237	2.14E6	1.0E-2	1.0E-5
Pu-238	87.75	4.7E-2	5.0E-7[b]
Pu-239	24131	1.4	1.5E-5[b]
Am-241	432.2	2.7E1	2.7E-2
Am-243	7.38E3	2.1E-3	2.1E-6
Cm-244	18.11	6.1	6.1E-3
UNID[e]	-	8.4E3	8.4

[a]Values are for wastes from X-10 site, except as noted; concentrations are corrected for radioactive decay assuming facility failure at 100 years after disposal.

[b]Value based on solubility limit in Table 5.

[c]Value for wastes from K-25 site.

[d]Value for wastes from Y-12 site.

[e]Denotes unidentified activity which is assumed to decay with half-life of 30 years.

Table 7. Assumptions regarding transport of waste leachate from shallow trenches through unsaturated soil to underlying aquifer

Group	Elements	Kd[a] (L/kg)	Concentration ratio[b]	Time[c] (y)
1	H	0	5.0E-1	7
2	Tc, U	1	4.5E-2	90
3	C, Np	10	4.1E-3	800
4	Be, Co, Ni, Sr, Sn, Sm, Eu, Am	690	6.0E-5	50,000
5	Cm	1,200	3.4E-5	80,000
6	Zr, Cs, Th, Pu	11,000	3.7E-6	800,000

[a]Equilibrium distribution coefficient.

[b]Concentration in underlying aquifer relative to solution concentration in disposal facility assuming no radioactive decay during transport to aquifer.

[c]Time after facility failure at which maximum concentration in underlying aquifer occurs.

Table 8. Results of dose analysis for groundwater pathway for disposal in shallow trenches[a]

Nuclide	Maximum concentration[b] (μCi/L)	Dose factor[c] (rem per μCi/L)	Maximum annual dose (mrem)
H-3	1.0E-1	3.2E-2	3
C-14	1.0E-2	9.3E-1	10
Tc-99	2.0E-2	6.4E-1	12
	3.6E-1[d]		230[d]
U-233	1.8E-4	1.1E2	20
U-234	5.0E-4[d]	1.1E2	55[d]
	1.9E-4[e]		20[e]
U-235	7.7E-5	9.8E1	8
	3.0E-5[d]		3[d]
	8.6E-6[e]		1[e]
U-238	1.5E-4	9.9E1	15
	1.7E-4[d]		17[d]
	1.7E-4[e]		17[e]
Others			<1

[a]Results are for wastes from X-10 site, except as noted, and apply to off-site individuals or inadvertent intruders.

[b]Concentration in aquifer at point of use.

[c]Annual effective dose equivalent per unit concentration in water obtained from Table A-20 of ref. [6].

[d]Value for wastes from K-25 site.

[e]Value for wastes from Y-12 site.

Table 9. Results of dose analysis for surface water pathway for disposal in above-grade tumuli[a]

Nuclide	Maximum concentration[b] (μCi/L)	Dose factor[c] (rem per μCi/L)	Maximum annual dose (mrem)
C-14	2.5E-2	9.3E-1	23
Sr-90	2.7E-2	5.7E1	1,500
Tc-99	3.9E-3	6.4E-1	3
	7.2E-2[d]		46[d]
Cs-137	5.4E-2	2.6E1	1,400
Eu-152	3.3E-2	2.4	80
Eu-154	2.9E-3	3.5	10
U-233	3.6E-5	1.1E2	4
U-234	1.0E-4[d]	1.1E2	11[d]
	3.7E-5[e]		4[e]
U-235	1.5E-5	9.8E1	1
	6.0E-6[d]		<1[d]
	1.7E-6[e]		<1[e]
U-238	3.1E-5	9.9E1	3
	3.4E-5[d]		3[d]
	3.4E-5[e]		3[e]
Am-241	2.5E-4	1.6E3	400
Cm-244	5.5E-5	8.5E2	47
UNID[f]	7.6E-2	4.0E1	3,000
Others			<1

[a]Results are for wastes from X-10 site, except as noted, and apply to off-site individuals or inadvertent intruders.

[b]Concentration in surface stream at point of use.

[c]Annual effective dose equivalent per unit concentration in water obtained from Table A-20 of ref. [6].

[d]Value for wastes from K-25 site.

[e]Value for wastes from Y-12 site.

[f]Denotes unidentified activity which is assumed to be mixture of Sr-90 and Cs-137.

Table 10. Results of dose analysis for inadvertent intrusion into waste disposal facility[a]

Nuclide	Maximum concentration[b] (μCi/m^3)	Dose factor[c] (rem per μCi/m^3)	Maximum annual dose (mrem)
H-3	3.1E2	3.9E-6	1
Be-10	4.6E3	2.2E-5	100
C-14	2.8E3	1.1E-6	3
Co-60	8.7E-1	3.7E-3	3
Sr-90	3.0E3	2.9E-4	870
Tc-99	4.3E2	9.4E-5	40
	7.9E3[d]		740[d]
Cs-137	5.9E3	8.2E-4	4,800
Eu-152	3.6E3	1.6E-3	5,800
Eu-154	3.2E2	1.8E-3	580
Th-232	3.5E1	4.5E-3	160
U-233	2.6E3	1.2E-5	31
U-234	4.5E1[d]	1.2E-5	<1[d]
	1.2E2[e]		1[e]
U-235	1.1E3	1.4E-4	150
	2.7[d]		<1[d]
	5.7[e]		1[e]
U-238	2.3E3	3.5E-5	81
	1.5E1[d]		<1[d]
	1.1E2[e]		4[e]
Am-241	2.7E1	7.0E-5	2
UNID[f]	8.4E3	5.6E-4	4,700
Others			<1

[a]Results are for wastes from X-10 site, except as noted, and apply to shallow trenches or above-grade tumuli.

[b]Concentration in solid waste at time of intrusion.

[c]Annual effective dose equivalent per unit concentration in solid waste obtained from Table A-21 of ref. [6].

[d]Value for wastes from K-25 site.

[e]Value for wastes from Y-12 site.

[f]Denotes unidentified activity which is assumed to be mixture of Sr-90 and Cs-137.