WASTE-ACCEPTANCE CRITERIA FOR RADIOACTIVE WASTE DISPOSAL

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ABSTRACT

A method has been developed for establishing waste-acceptance criteria based on quantitative performance factors that characterize the confinement capabilities of a disposal facility for radioactive waste. The method starts from the basic objective of protecting public health and safety by assuring that disposal of the waste will not result in a radiation dose to any member of the general public, in either the short or long term, in excess of an established basic dose limit. A key aspect of the method is the introduction of a confinement factor that characterizes the overall confinement capability of a particular disposal facility and can be used for quantitative performance assessments as well as for establishing facility-specific waste-acceptance criteria. Confinement factors enable direct and simple conversion of a basic dose limit into waste-acceptance criteria, specified as concentration limits on radionuclides in the waste streams. Waste-acceptance criteria can be represented visually as activity/time plots for various waste streams. These plots show the concentrations of radionuclides in a waste stream as a function of time and permit a visual, quantitative assessment of long-term performance, relative risks from different radionuclides in the waste stream, and contributions from ingrowth. Application of the method to generic facility designs provides a rational basis for a waste classification system.

INTRODUCTION

The basic objective of radioactive waste management is to protect public health and safety. For this objective to be achieved, procedures must be established for ensuring compliance with basic radiation protection criteria and for reducing detrimental effects of waste disposal to levels that are as low as reasonably achievable (ALARA). The procedures must enable a quantitative assessment of the extent to which a disposal site and facility can realize the basic performance requirements. This paper presents a method for deriving performance requirements from radiation protection standards. The results are presented in a manner intended to provide a clear picture of the relationship among waste characteristics, critical features of the site and facility design, and the long-term performance of the disposal facility.

A basic radiation dose limit, expressed as an effective dose-equivalent commitment (1) and applied to a member of a critical population group (Ref. 1, Par. 71), provides a well-defined standard for assessing the performance of a disposal system. The potential dose (attributable to the disposed waste) to a member of a critical population group will depend on the confinement capabilities of the disposal facility and the characteristics of the waste placed in the facility. The criteria for compliance with the basic dose limit may, therefore, be reformulated as a problem of establishing site-specific, risk-based waste-acceptance limits such that the dose limit will not be exceeded if the waste-acceptance limits are met. These waste-acceptance limits are expressed in terms of radionuclide concentrations in the waste. Establishment of waste-acceptance limits requires that a quantitative relationship be derived among the dose to a member of a critical population group, disposal system features, and waste characteristics. The problem is further complicated by the need to estimate the projected risk several hundred years or more into the future.

Pathway analysis is used to derive the relationship between the dose and the system and waste characteristics. Extensive effort has been devoted to pathway analysis over the past two decades, and a number of models and codes are available for carrying out such analyses (2-7). A problem in applying these results is that the models and codes are complex, and it is not easy -- even for experts -- to identify the critical parameters and quantitative relationships that determine performance.

This problem may be made more tractable by defining a single quantity -- referred to as the "confinement factor" -- to provide an overall measure of the confinement capabilities of a disposal facility. This factor, as defined below, provides a simple and direct means for (a) deriving waste-acceptance criteria from a basic dose limit; (b) comparing the performance of different sites and facility designs; (c) representing, visualizing, and taking into account the time dependence of the disposal-facility confinement capabilities and of the waste hazard; and (d) separating the effects of site features and facility design features on performance and establishing a quantitative relationship between performance and parameters that characterize the site and facility design. Although used here only to relate site and facility design features to the long-term (>100 yr) public risk, a factor analogous to the confinement factor could also be defined and used to establish criteria for limiting the short-term occupational risk.

Although compliance with site-specific waste-acceptance criteria is a necessary and sufficient condition for ensuring adequate protection of public health and safety following disposal, a generic waste classification system is still needed for regulating radioactive waste disposal. Risk-based waste classification criteria may be regarded as generic waste-acceptance criteria. Because the risk subsequent to disposal is determined by the confinement capability of the disposal facility used, risk-based waste classes are necessarily related to disposal facility categories: e.g., a sanitary landfill for waste with radionuclide concentrations below regulatory concern, shallow-land burial for low-level waste, greater-confinement disposal for intermediate-level waste, and a deep geologic repository for high-level waste. A risk-based waste classification system can be developed by deriving a confinement factor for a prototype facility for each category and using these prototype confinement factors to derive waste class limits from a basic dose limit. A similar waste classification system has been proposed by Cohen and Smith (8).

THE CONFINEMENT FACTOR

The fundamental health and safety requirement that the basic dose limit shall not be exceeded at any time within the time horizon can be expressed by the following inequality:

$$H_E(t) \le H_{EL}, \quad 0 \le t \le T_h \qquad (1)$$

where:

$H_E(t)$ = annual committed effective dose equivalent to a member of the critical population group at time t following disposal,

H_{EL} = basic dose limit, and

T_h = time horizon.

For the purpose of establishing waste-acceptance criteria, the radioactivity in a waste stream can be characterized by the total weighted radionuclide concentration:

$$C(t) = \sum_i w_i \times C_i(t) \qquad (2)$$

where the summation is over all the radionuclides in the waste stream and

$C_i(t)$ = activity concentration of the i^{th} radionuclide in the waste and

w_i = weighting factor.

The confinement capabilities of a disposal facility can be characterized by a facility-specific confinement factor:

$$F(t) = H_E(t)/C(t) \qquad (3)$$

where:

$H_E(t) = \sum_i F_i(t) \times C_i(t)$ = annual committed effective dose equivalent for all radionuclides in the waste,

$F_i(t) = H_{Ei}(t)/C_i(t)$ = facility-specific confinement factor for i^{th} radionuclide at time t following disposal, and

$H_{Ei}(t)$ = annual committed effective dose equivalent for i^{th} radionuclide.

The confinement factor will depend on the exposure scenario; location of the exposed individual; site, design, and operating variables; dosimetry model parameters; and waste parameters. The critical population group used in the scenario for deriving the waste-acceptance criteria is usually assumed to consist of a family that establishes residence and a family vegetable garden on the site after the controls have lapsed.

The time dependence of the confinement factors will be from (a) deterioration of the engineered confinement barriers and (b) the rate of transport and dilution of radionuclides that escape confinement. If the cover is thick enough to provide the requisite shielding, the confinement factor will be nil immediately following disposal in the sense that the dose to any member of the general public will be immeasurably small, even for waste that is highly radioactive. The confinement factor will remain negligible for a time $T_b = T_b(\text{barrier}) + T_b(\text{delay})$, where $T_b(\text{barrier})$ is the time at which the engineered barriers begin to deteriorate and $T_b(\text{delay})$ is the time for radionuclides that escape confinement to reach a human exposure location.

Idealized representations of the time dependence of the confinement factors are shown in Fig. 1. The solid curve corresponds to the case in which confinement barriers deteriorate rapidly at the breakthrough time T_b. This is further idealized as an abrupt breakthrough, as shown by the dashed line. This idealized form is chosen because it leads to a very simple parametric representation of the confinement factor:

$$\begin{aligned} F(t) &= 0, \quad 0 \le t \le T_b \\ F(t) &= F_c, \quad T_b < t \le T_h \end{aligned} \qquad (4)$$

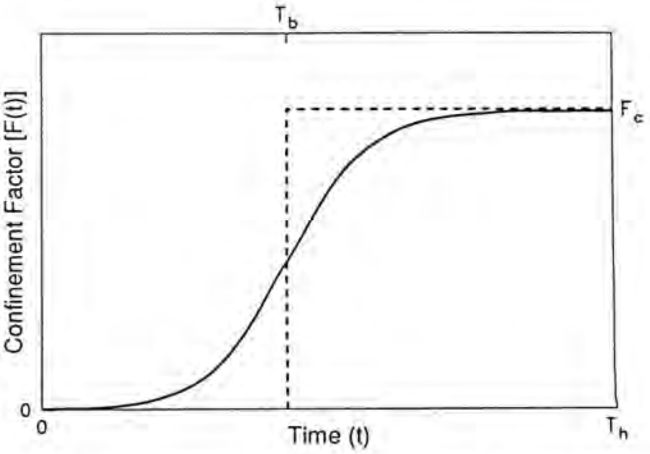

Fig. 1. Confinement Factors for Gradual (——) and Abrupt (- - -) Breakthrough.

where:

T_b = breakthrough time and

$F_c \equiv F(T_h)$ = limiting value of the confinement factor.

This idealized representation is a reasonable assumption for exposure due to intrusion, which is the controlling scenario used for establishing waste-acceptance criteria. If used for estimating radiological detriments, it is a very conservative assumption.

WASTE-ACCEPTANCE CRITERIA

Waste-acceptance criteria can now be formulated in terms of the radionuclide concentration limits. The confinement factor (Eq. 3) can be used to convert the basic dose limit (Eq. 1) to a concentration limit, as follows:

$$H_E(t) \leq H_{EL} \qquad (5)$$

$$H_E(t)/F(t) \leq H_{EL}/F(t) \qquad (6)$$

$$C(t) \leq C_L(t) \qquad (7)$$

where $C_L(t) \equiv H_{EL}/F(t)$ is the concentration limit curve.

An illustrative concentration-limit curve is shown in Fig. 2, together with hypothetical decay curves for two waste streams. One of these streams would be acceptable, because the decay curve lies entirely below the limit curve. The other would be unacceptable, because the decay curve lies above the limit curve for an interval of time between the breakthrough time and the time horizon. The limit curve represented by the solid line corresponds to the confinement factor represented by the solid line in Fig. 1. If the confinement factor is represented by the dashed line in Fig. 1, then the limit curve takes on the L-shaped form shown by the dashed line in Fig. 2, and the waste-acceptance criterion becomes:

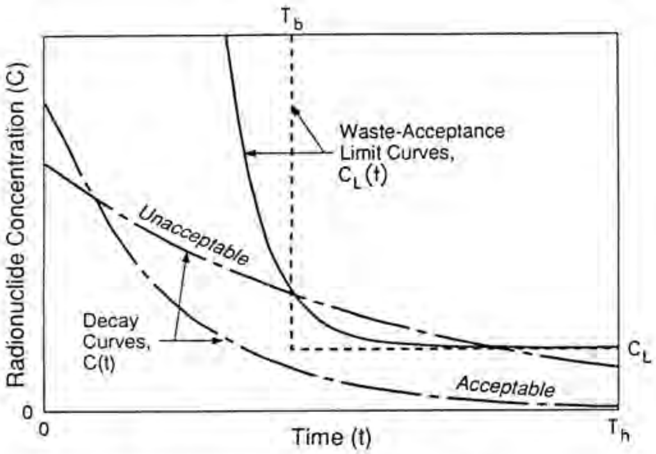

Fig. 2. Waste-Acceptance Limit Curves for Gradual (—) and Abrupt (- - -) Breakthrough and Decay Curves (——— — ———) for Acceptable and Unacceptable Waste Streams.

$$C(t) \leq C_L, \quad T_b \leq t \leq T_h \qquad (8)$$

where:

$C_L \equiv C_L(T_h) = H_{EL}/F_c$ = concentration limit at the time horizon and

T_b = breakthrough time.

The key quantities needed to convert dose limits to concentration limits are the facility-specific, single-radionuclide confinement factors, $F_i(t)$, and the weighting factors, w_i. The confinement factors are derived by means of a pathway analysis and can be expressed as follows:

$$F_i(t) = \sum_s \sum_p P_s \times F_{d,ip} \times F_{e,sip}(t) \times F_{b,sip}(t) \qquad (9)$$

where the sum is over exposure scenarios (s) and pathways (p) and

P_s = probability that an exposure scenario will be realized,

$F_{d,ip}$ = dose conversion factor (a measure of the severity of the health effects),

$F_{e,sip}$ = environmental transport factor (a measure of the confinement effectiveness of the disposal site and surrounding environment), and

$F_{b,sip}$ = barrier factor for engineered confinement barriers (a measure of the confinement effectiveness of the engineered features of a disposal facility).

Weighting factors may be chosen in different ways. The simplest and most widely used choice is:

$$w_i = 1 \qquad (10)$$

for all radionuclides in the waste stream. The total concentration C(t) obtained with these weighting factors corresponds to the "Curie content" of the waste and will be referred to as the unweighted concentration. In this case, the choice of normalization is such that:

$$\sum_i w_i = N \qquad (11)$$

where N is the total number of radionuclides in the waste stream.

Another choice is to make the weights proportional to single-radionuclide confinement factors at the time horizon, or:

$$w_i = F_i(T_h)/F(T_h) \qquad (12)$$

with normalization given by Eq. 11. The total confinement factor is then the waste-stream average over the individual confinement factors:

$$F(T_h) = (1/N) \sum_{i=1}^{N} F_i(T_h) \qquad (13)$$

and the total concentration limit, C_L, can be expressed in terms of individual radionuclide concentration limits, C_{Li}, as:

$$(1/C_L) = (1/N) \sum_{i=1}^{N} (1/C_{Li}) \tag{14}$$

where $C_{Li} = H_{EL}/F_i(T_h)$. This leads to the familiar sum-of-fractions rule:

$$\sum_i C_i(t)/C_{Li} \leq 1 \tag{15}$$

This choice of the weights (Eq. 12) makes the confinement factor (F), the weights (w_i), and the concentration limit (C_L) both waste- and facility-dependent.

Because the choice of normalization is arbitrary, it may be convenient to select it so that F and w_i are independent of the mixture of radionuclides in the waste stream and are characteristics of the disposal facility alone (for a waste stream with given chemical and physical properties). This can be accomplished by choosing the normalization such that

$$F(T_h) = (1/N_T) \sum_{i=1}^{N_T} F_i(T_h) \tag{16}$$

where N_T is the total number of radionuclides accepted at the facility.

Equations 12 and 16 give weighting factors that are independent of the mixture of radionuclides in the waste stream. The weighting factors still depend on the facility and the chemical and physical properties of the waste, because the single-radionuclide confinement factors, $F_i(t)$, depend on these quantities. This causes no difficulty for waste-acceptance criteria, which are facility-specific and include specifications regarding acceptable chemical and physical properties. Facility-dependent weighting cannot, however, be used to define classes for a waste-classification system; for this use, the weighting factors must be mixture-independent and also facility-independent. This can be accomplished by replacing the facility-dependent environmental transport and barrier factors with average values. The weighting factors would still be proportional to the radionuclide-dependent dose conversion factors.

ACTIVITY/TIME PLOTS

The use of waste-acceptance criteria is illustrated here by applying them to typical waste streams. The waste streams are represented by diagrams plotting radioactivity vs. time (activity/time plots), shown in Figs. 3-6. These diagrams are obtained by ordering the radionuclides in the waste stream according to increasing half-life and then plotting partial sums: $w_1C_1(t)$, then $w_1C_1(t) + w_2C_2(t)$, then $w_1C_1(t) + w_2C_2(t) + w_3C_3(t)$, etc. The outermost curve is the total radioactivity C(t). The activity/time plots can be used to ascertain at a glance the relative contributions from different radionuclides at different times. The vertical distance between any two curves at any time corresponds to the fractional weighted concentration of that radionuclide in the waste stream. In Figs. 3 and 5, the unweighted concentrations are plotted ($w_i = 1$); Figs. 4 and 6 show the weighted concentrations, with the weights given by Eq. 12.

Two waste-acceptance limits are needed: a limit for shallow-land burial (SLB) and a limit for greater-confinement disposal (GCD). The simplified, L-shaped form represented by the dashed line in Fig. 2 is chosen for the concentration limit curve. Therefore, to specify the SLB limit and the GCD limit, two quantities are needed for each: the breakthrough times (T_{SLB} and T_{GCD}) and the concentration limits at the time horizon (C_{SLB} and C_{GCD}).

Data on breakthrough times for representative SLB and GCD facilities are lacking; therefore, for illustrative purposes, the breakthrough times are inferred from time boundaries established for general use. Two time boundaries for commercial low-level waste for which precedents have been established in regulatory usage (9) are (a) the time during which active institutional control can be assumed, 100 yr [10 CFR 61.7(b)(4)], and (b) the design life for intruder barriers, 500 yr [10 CFR 61.52(a)(92)]. It is reasonable to set the SLB breakthrough time equal to the duration of institutional controls (T_{SLB} = 100 yr). A conservative estimate for the GCD breakthrough time is the design life for intruder barriers for commercial class C-waste (T_{GCD} = 500 yr).

For unweighted concentration limits, the following illustrative values were chosen:

$$C_{SLB} = 0.01 \text{ Ci/m}^3 \text{ and } C_{GCD} = 10 \text{ Ci/m}^3 \tag{17}$$

The choice of these values is somewhat arbitrary, although some justification has been provided by Gilbert et al. (10,11). The values $C_{SLB} = 0.1$ Ci/m^3 and $C_{GCD} = 10$ Ci/m^3 have been suggested by Cohen and Smith (8).

For the weighted concentration limits, an estimate may be obtained by introducing the simplifying approximations that the environmental transport factors and barrier factors in Eq. 9 are the same for all radionuclides and that the dominant pathway is the ingestion pathway. The single-radionuclide confinement factors at the time horizon can then be written as follows:

$$F_i(T_h) = F_{di} \times \langle F_e(T_h) \times F_b(T_h) \rangle \tag{18}$$

where:

F_{di} = dose conversion factor for ingestion for the i^{th} radionuclide and

$\langle F_e(T_h) \times F_b(T_h) \rangle$ = average product of the environmental transport and barrier factors for the ingestion pathways for all radionuclides.

For the case in which all engineered barriers have failed (12,13) it has been estimated that the product of the enviromental transport factors and the barrier factors is $\langle F_e(T_h) \times F_b(T_h) \rangle = 10^{-3}$ m^3/yr. Using this value, the dose conversion factors derived by means of dosimetry models recommended by the ICRP (1979-82), and a dose limit of H_{EL} = 100 mrem/yr, SLB

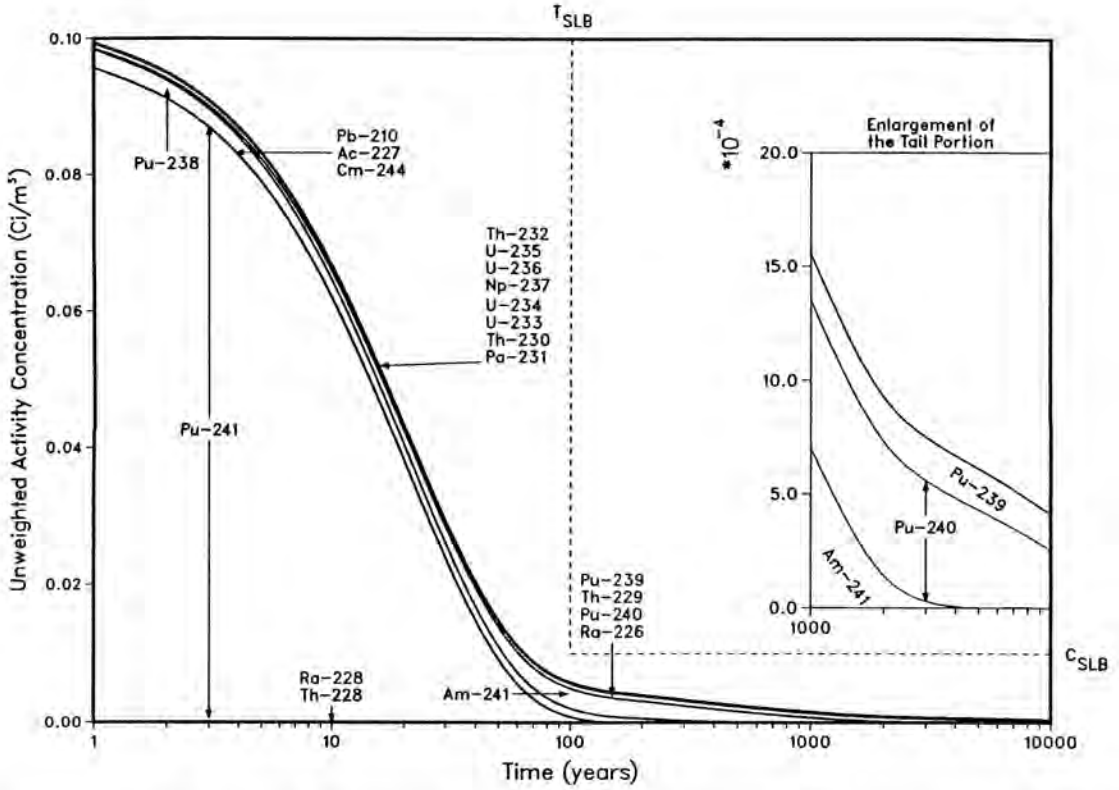

Fig. 3. Representative Radionuclide Composition (unweighted concentrations) as a Function of Time for DOE/Defense Alpha Low-Level Waste (total initial concentration = 0.104 Ci/m^3, C_{SLB} = 0.01 Ci/m^3, C_{GCD} = 10 Ci/m^3).

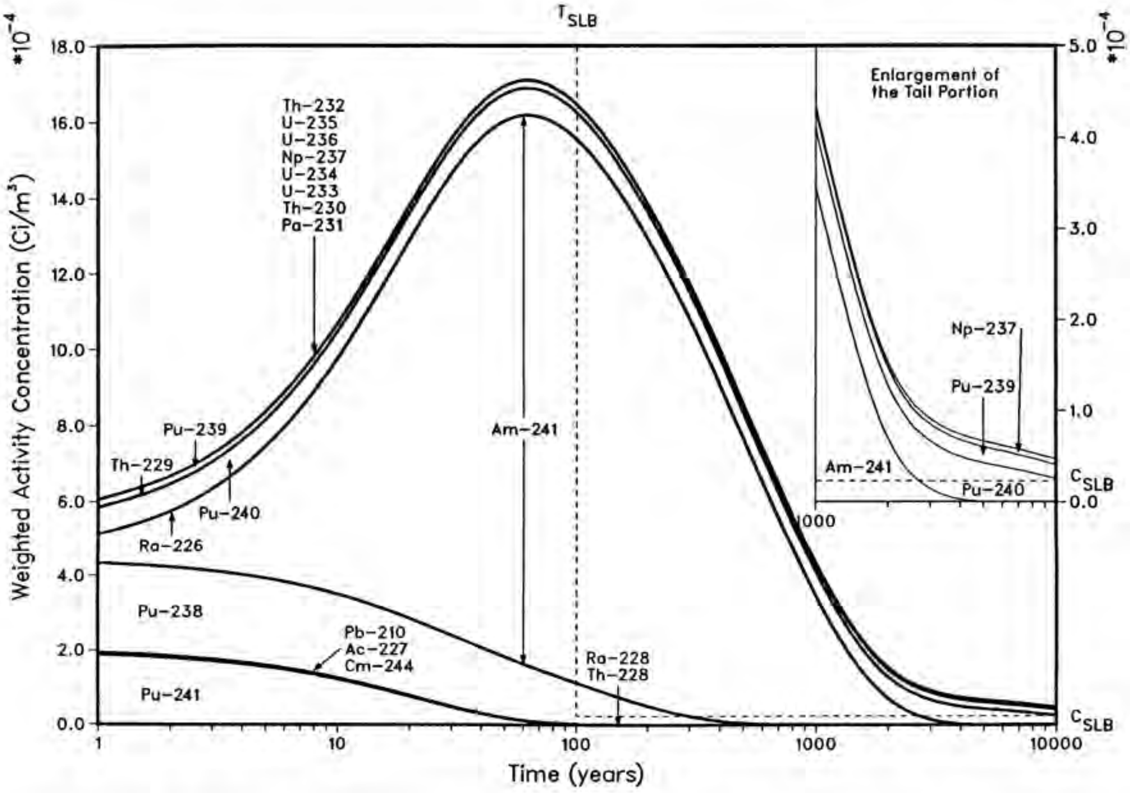

Fig. 4. Representative Radionuclide Composition (weighted concentrations) as a Function of Time for DOE/Defense Alpha Low-Level Waste (C_{SLB} = 0.000022 Ci/m^3, C_{GCD} = 0.022 Ci/m^3).

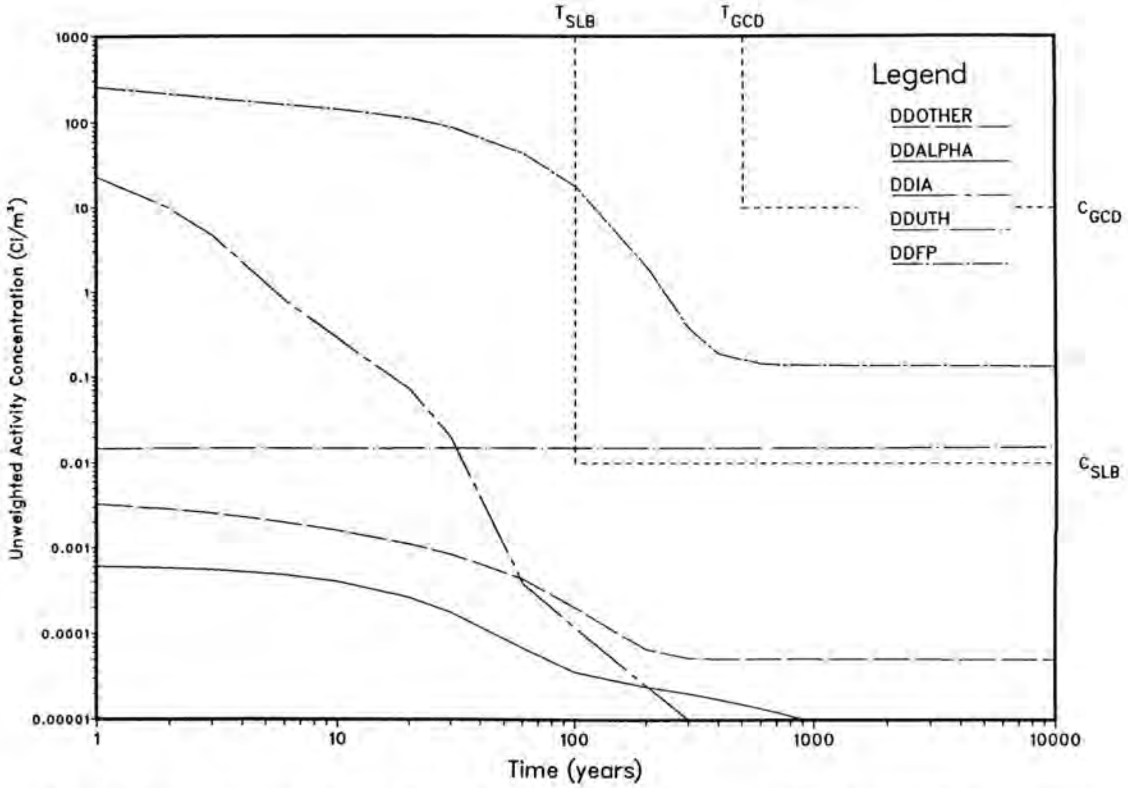

Fig. 5. Total Unweighted Activity Concentrations as a Function of Time for DOE/Defense Low-Level Waste Streams (C_{SLB} = 0.01 Ci/m^3, C_{GCD} = 10 Ci/m^3).

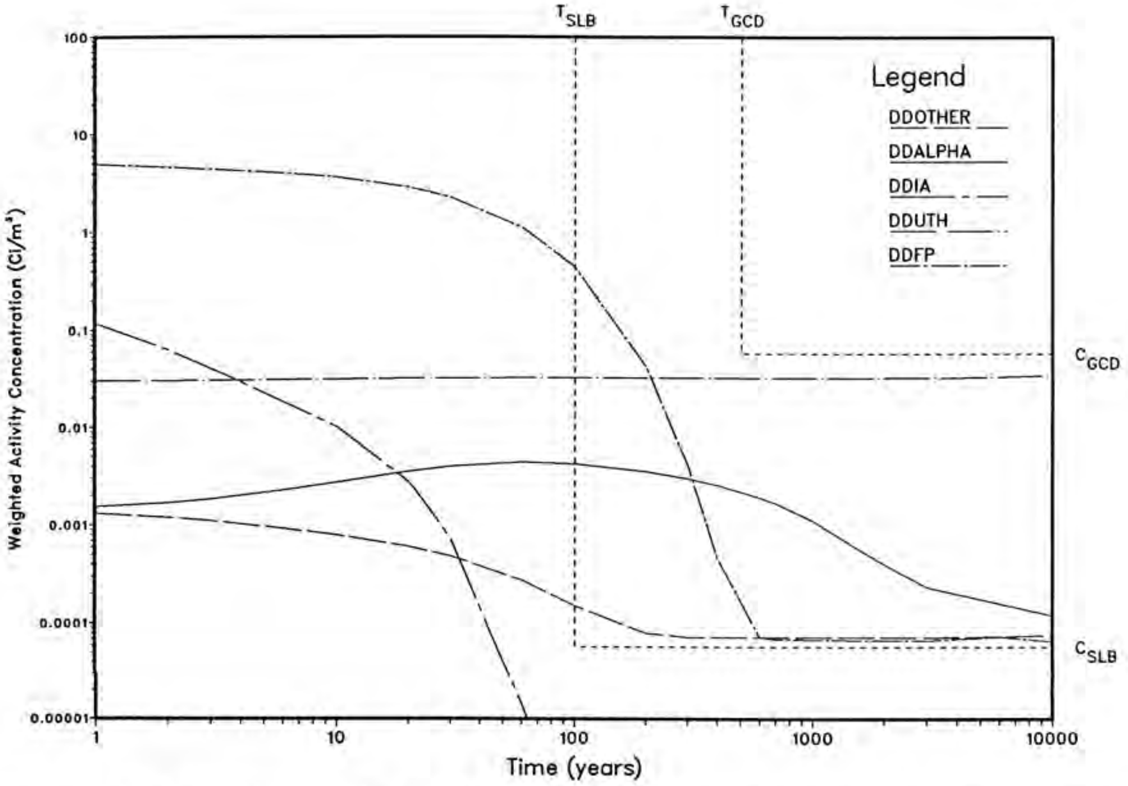

Fig. 6. Total Weighted Activity Concentrations as a Function of Time for DOE/Defense Low-Level Waste Streams (C_{SLB} = 0.000057 Ci/m^3, C_{GCD} = 0.057 Ci/m^3).

concentration limits, C_{SLB}, can be obtained for the weighted case. For the purpose of illustration, it has been assumed that the GCD concentration limit, C_{GCD}, is 1,000 times larger than C_{SLB}. A better estimate would require more detailed knowledge (not available at this time) of the long-term behavior of the barrier factors.

Figures 3 and 4 show one of the U.S. Department of Energy defense-waste streams, the DOE/Defense alpha waste (14). The SLB and GCD concentration limits are also shown on these plots. Weighted concentrations (Fig. 4) are computed using the normalization factor given by Eq. 11, making the limits both mixture- and facility-dependent. This waste stream illustrates the significance of looking at weighted as well as unweighted concentrations. If only the unweighted activity concentrations (Fig. 3) were considered, one would conclude that all concentrations lie below the illustrative SLB limit at all times. However, the weighted concentration plot (Fig. 4) shows that this waste stream exceeds the SLB concentration limit. The main reason for this is the significant ingrowth of Am-241, which also has a comparatively large dose conversion factor.

Figures 5 and 6 show total concentrations as a function of time for five representative DOE/Defense waste streams. (The abbreviations used are fission products, DDFP; uranium/thorium, DDUTH; induced activity, DDIA; alpha, DDALPHA; and other, DDOTHER). Figure 5 shows the unweighted concentrations, as well as total radionuclide concentration limits, for SLB and GCD. From this plot, one would infer that uranium/thorium and fission-product wastes would be candidates for GCD if the illustrative value for C_{SLB} were applicable. [It may be noted that the illustrative value for C_{SLB} is quite conservative. The value $C_{SLB} = 0.1\ Ci/m^3$ suggested by Cohen and Smith (8) would place the unweighted concentration curve for uranium/thorium wastes below the SLB limit.] Figure 6 shows the total weighted concentrations as a function of time for all five waste streams. The choice of normalization for this figure is different from the one used in previous plots. For this case, the value leading to Eq. 16 has been used, making the concentration limits (C_{SLB} and C_{GCD}) the same for all waste streams. The weighted concentration plot suggests that all the waste streams except induced-activity wastes might be candidates for GCD.

It should be emphasized that the values for C_{SLB} and C_{GCD} are illustrative only; hence, it should not be inferred that waste streams with total activity concentrations exceeding C_{SLB} in the above examples require GCD, or that those with concentrations exceeding C_{GCD} should be disposed of as high-level waste. In actual application, SLB and GCD concentration limits should be calculated by means of site-specific pathway analyses.

Activity/time plots for other waste streams and a more detailed discussion of the methodology may be found in the reports on which this paper is based (10,11).

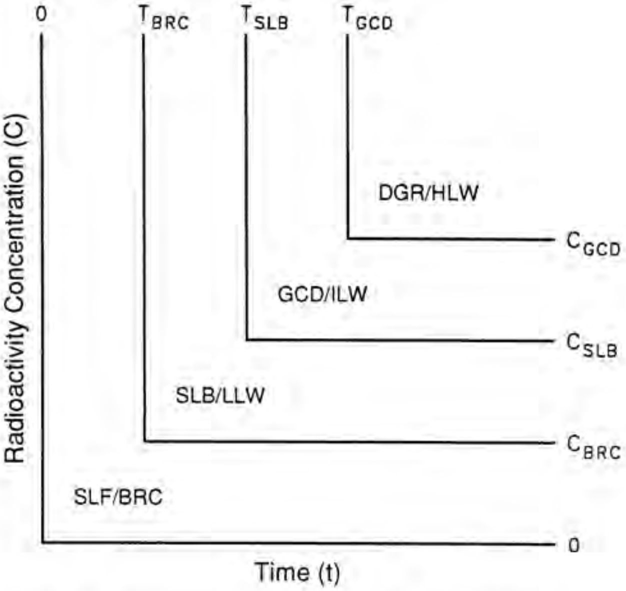

Fig. 7. Activity/Time Boundaries for a Risk-Based Waste-Classification System

RISK-BASED WASTE-CLASSIFICATION SYSTEM

The foregoing method can also be used to establish a risk-based waste-classification system. The waste-class boundaries would be defined on an activity/time diagram by means of the same two parameters used for waste-acceptance criteria for the case of abrupt breakthrough: a breakthrough time, T_b, and a long-term concentration limit, C_L. The L-shaped activity/time SLB and GCD limits shown in Fig. 7 form natural boundaries between three types of wastes: low-level (LLW), intermediate-level (ILW), and high-level (HLW). A corresponding boundary for a sanitary landfill (SLF) could be used to establish a limit for waste with radionuclide concentrations below regulatory concern (BRC). Prototype SLF, SLB, and GCD facilities would have to be specified in order to derive quantitative risk-based values. Provisional values based on current practice have been suggested by Cohen and Smith (8).

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