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WASTE-ACCEPTANCE CRITERIA FOR GREATER-CONFINEMENT DISPOSAL

T.L. Gilbert and N.K. Meshkov *
Energy and Environmental Systems Division
Argonne National Laboratory
Argonne, Illinois 60439

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ABSTRACT

A methodology for establishing waste-acceptance criteria based on quantitative performance factors that characterize the confinement capabilities of a waste-disposal site and facility has been developed. The methodology starts from the basic objective of protecting public health and safety by providing assurance 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. The method is based on an explicit, straightforward, and quantitative relationship among individual risk, confinement capabilities, and waste characteristics. A key aspect of the methodology is the introduction of a confinement factor that characterizes the overall confinement capability of a particular facility and can be used for quantitative assessments of the performance of different disposal sites and facilities, as well as for establishing site-specific waste-acceptance criteria. Confinement factors are derived by means of site-specific pathway analyses. They make possible a direct and simple conversion of a basic dose limit into waste-acceptance criteria, specified as concentration limits on radionuclides in the waste streams and expressed in quantitative form as a function of parameters that characterize the site, facility design, waste containers, and waste form. 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.

INTRODUCTION

The basic objective of radioactive waste management is protection of 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 are capable of realizing 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 among the dose to a member of a critical population group, disposal system features, and waste characteristics be derived. The problem is further complicated by the fact that estimates of the projected risk several hundred years or more into the future are required.

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 (1) deriving waste-acceptance criteria from a basic dose limit;

(2) comparing the performance of different sites and facility designs; (3) representing, visualizing, and taking into account the time dependence of the disposal-facility confinement capabilities and of the waste hazard; and (4) separating the effects of site features and facility design features on performance and establishing a quantitative relation 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 years) 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.

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:

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

where:

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

H_{EL} = basic dose limit

T_h = time horizon

A typical waste stream is composed of several radionuclides. It is convenient to define the total radionuclide concentration for the waste stream, C(t), as

$$C(t) = \sum_i w_i \times C_i(t) \tag{2}$$

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

$C_i(t)$ = activity concentration of ith radionuclide in waste

w_i = weighting factor

In order to characterize the confinement capabilities of a disposal system, a system-specific confinement factor is defined, as follows:

$$F(t) = H_E(t)/C(t) \tag{3}$$

where:

$H_E(t) = \sum_i F_i(t) \times C_i(t)$ = annual effective dose-equivalent commitment for all radionuclides in the mixture

$F_i(t) = H_{Ei}(t)/C_i(t)$ = system-specific confinement factor for the ith radionuclide at time t following disposal

$H_{Ei}(t)$ = annual effective dose-equivalent commitment for ith radionuclide

The confinement factor will depend on the exposure scenario; the location of the exposed individual; the 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 garden on the site after the controls have lapsed.

The time dependence of the confinement factors will be from (1) deterioration of the engineered confinement barriers and (2) the rate of transport and dilution of radionuclides that escape confinement. If the cover is thick enough to provide the requisite shielding, then 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 engineering 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 rapid deterioration of confinement barriers occurs 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:

$$F(t) = 0, \qquad 0 \le t \le T_b \tag{4}$$

$$F(t) = F_c \qquad T_b < t \le T_h$$

where:

T_b = breakthrough time

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

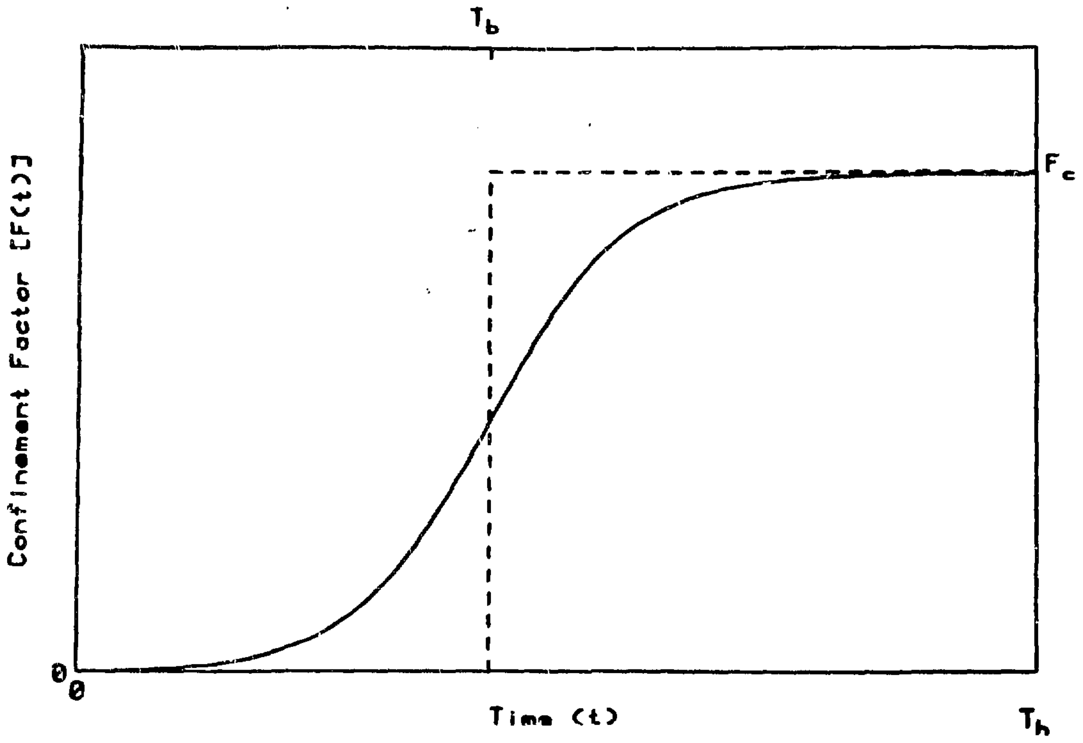

FIGURE 1 Confinement Factors for Gradual (——) and Abrupt (- - -) Breakthrough

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 the concentration limit, as follows:

$$H_E(t) \le H_{EL} \tag{5}$$

$$\downarrow$$

$$H_E(t)/F(t) \le H_{EL}/F(t) \tag{6}$$

$$\downarrow$$

$$C(t) \le C_L(t) \tag{7}$$

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

$$C(t) \le C_L, \qquad T_b \le t \le T_h \tag{8}$$

where:

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

T_b = breakthrough time

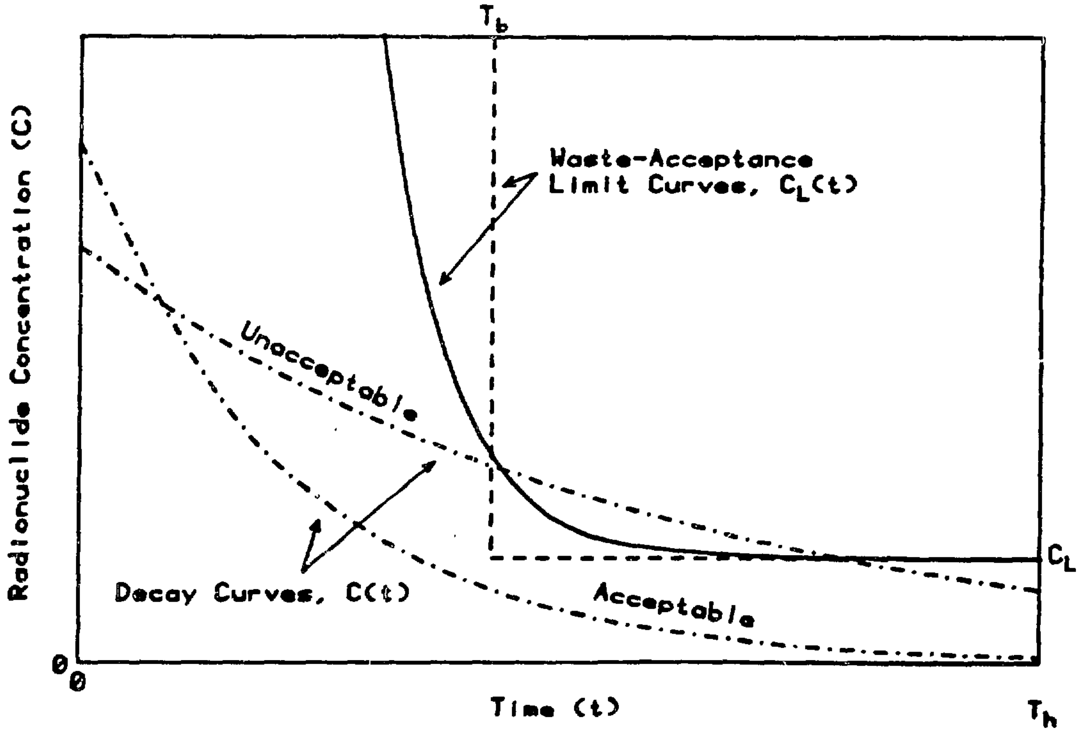

FIGURE 2 Waste-Acceptance Limit Curves for Gradual (——) and Abrupt (- - -) Breakthrough and Decay Curves (·–·–·) for Acceptable and Unacceptable Waste Streams

The key quantities needed for the conversion of dose limits to concentration limits are the system-specific, single-radionuclide confinement factors $F_i(t)$ and the weighting factors w_i. The system-specific, single-radionuclide confinement factors are derived by means of 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)

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

Weighting factors w_i may be chosen in different ways. The simplest and most widely used choice of the weighting factor 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 w_i proportional to single-radionuclide confinement factors F_i at the time horizon, or

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

with normalization given by Eq. 11. Then:

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

or the total confinement factor is the waste-stream average over the individual confinement factors. Also, the total concentration limit C_L can be expressed in terms of individual radionuclide concentration limits C_{Li} as

$$(1/C_L) = \sum_i (1/C_{Li})/N \tag{14}$$

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

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

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 the confinement factor F and the weights w_i are independent of the waste stream and are characteristics of the disposal facility alone. This can be accomplished by choosing the normalization such that

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

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

Equations 12 and 15 give weighting factors that are independent of the waste stream at the time horizon. The weighting factors are still facility-dependent, because the single-radionuclide confinement factors $F_i(t)$ are facility-dependent. This causes no difficulty for site-specific waste-acceptance criteria. Site- or facility-dependent weighting cannot, however, be used to define classes for a waste-classification system; for this use, the weighting factors must be waste-stream-independent and also site- and facility-independent. This can be accomplished by replacing the facility-dependent environmental transport and barrier factors by average (facility-independent) 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 are: (1) the time for which active institutional control can be assumed, 100 years [10 CFR 61.7(b)(4)]; and (2) the design life for intruder barriers, 500 years [10 CFR 61.52(a)(92)].[8] It is reasonable to set the SLB breakthrough time equal to the duration of institutional controls (T_{SLB} = 100 years). A conservative estimate for the GCD breakthrough time is the design life for intruder barriers for commercial class C-waste (T_{GCD} = 500 years).

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

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

The choice of these values is somewhat arbitrary, although some justification has been provided by Gilbert et al. (1986).

For the weighted concentration limits, an estimate may be obtained by introducing the simplifying approximations that 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:

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

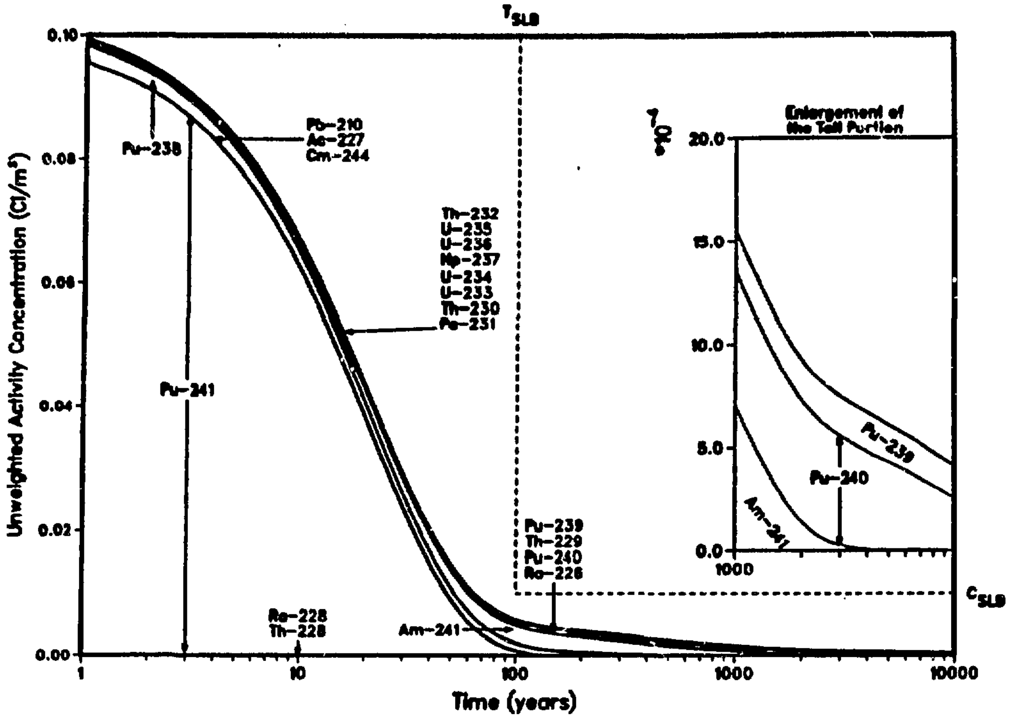

FIGURE 3 Representative Radionuclide Composition (unweighted concentrations) as a Function of Time for DOE/Defense Alpha Low-Level Waste (Total initial concentration = 0.104 Ci/m^3, C_{SLB} = 0.01 Ci/m^3, C_{GCD} = 10 Ci/m^3)

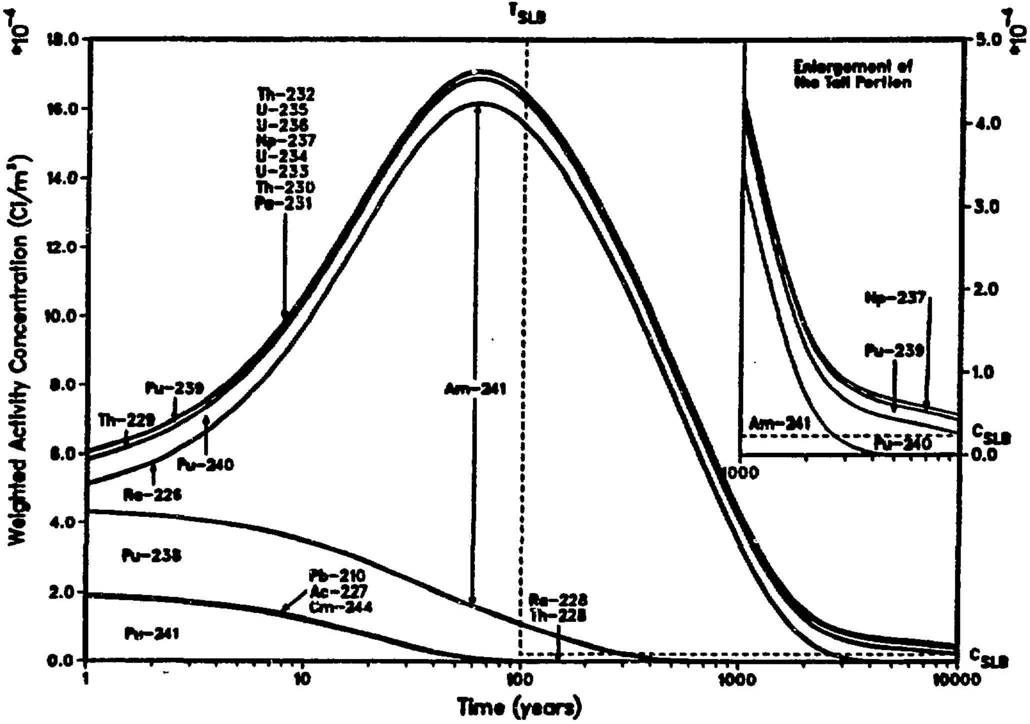

FIGURE 4 Representative Radionuclide Composition (weighted concentrations) as a Function of Time for DOE/Defense Alpha Low-Level Waste (C_{SLB} = 0.000022 Ci/m^3, C_{GCD} = 0.022 Ci/m^3)

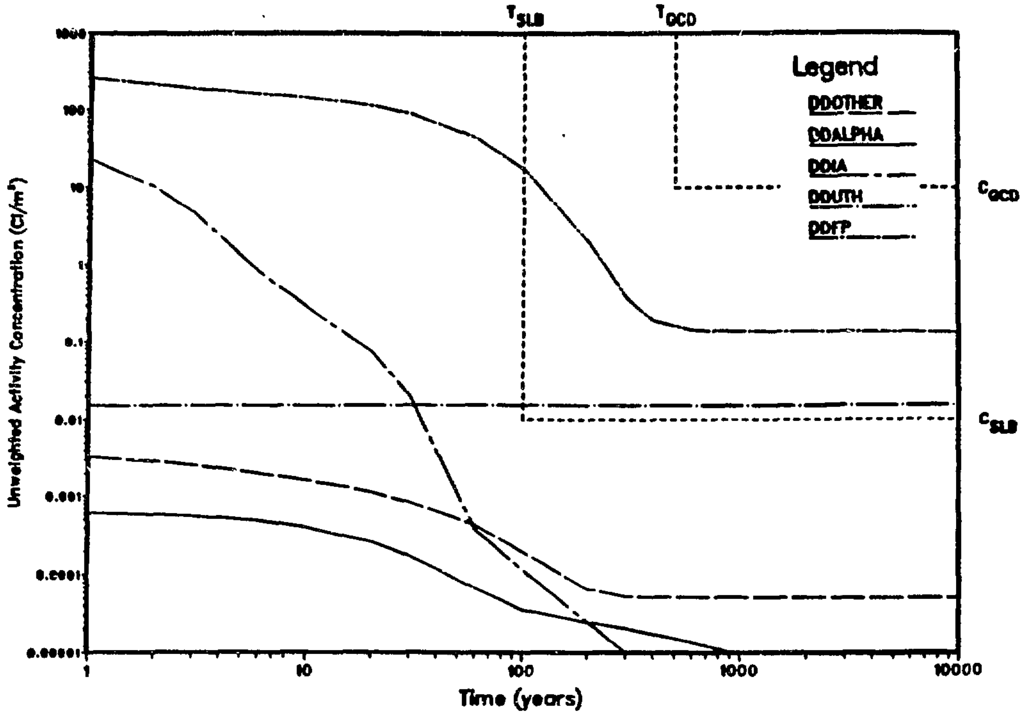

FIGURE 5 Total Unweighted Activity Concentrations as a Function of Time for DOE/Defense Low-Level Waste Streams (C_{SLB} = 0.01 Ci/m^3, C_{GCD} = 10 Ci/m^3)

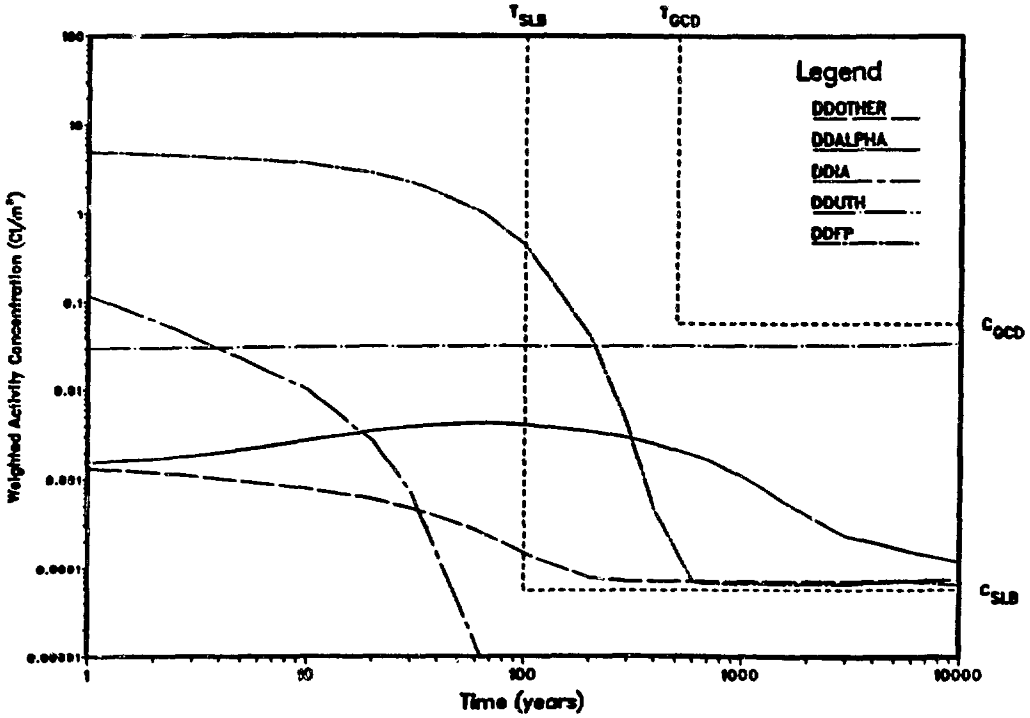

FIGURE 6 Total Weighted Activity Concentrations as a Function of Time for DOE/Defense Low-Level Waste Streams (C_{SLB} = 0.000057 Ci/m^3, C_{GCD} = 0.057 Ci/m^3)

where:

F_{di} = dose conversion factor for ingestion for the ith radionuclide

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

It has been estimated for the case that all engineered barriers have failed[9-11] 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 and the dose conversion factors derived by means of dosimetry models recommended by the ICRP (1979-82) and a dose limit H_{EL} = 100 mrem/yr, SLB 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/Department of Defense (DOE/Defense) waste streams, the DOE/Defense alpha waste.[12] 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 waste-stream- and facility-dependent. This waste stream illustrates dramatically 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 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. 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 would 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.

RISK-BASED WASTE-CLASSIFICATION SYSTEM

The foregoing methodology 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

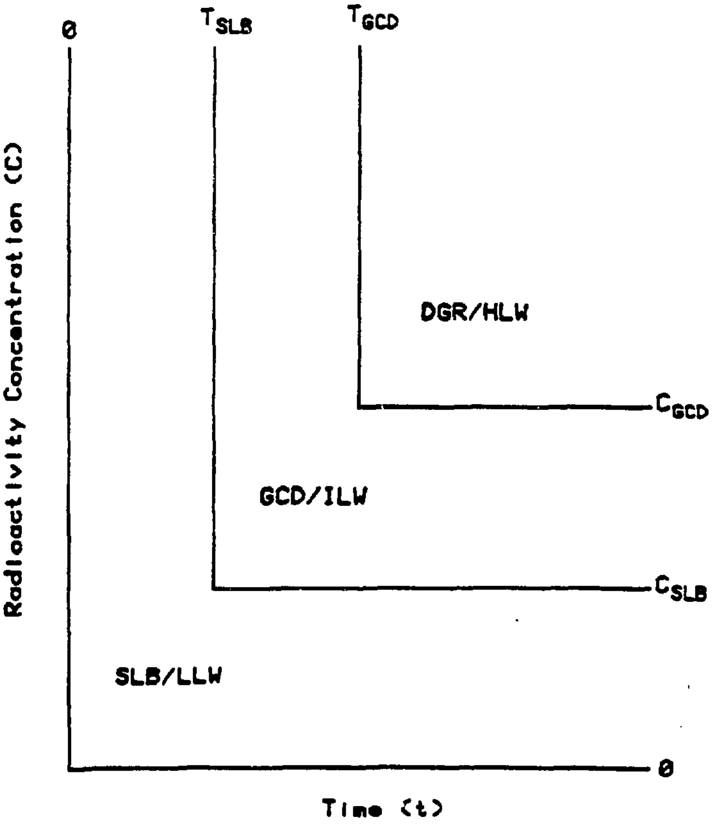

FIGURE 7 Activity/Time Boundaries for a Risk-Based Waste-Classification System

between three types of wastes: low-level (LLW), intermediate-level (ILW), and high-level (HLW). A similar waste-classification system has also been proposed.[13]

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