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PARAMETRIC STUDY OF GEOHYDROLOGIC PERFORMANCE CHARACTERISTICS FOR GEOLOGIC WASTE REPOSITORIES

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ABSTRACT

One of the major objectives of the National Waste Terminal Storage Program is to identify potential geologic sites for storage and isolation of radioactive waste (and possibly irradiated fuel).

Potential sites for the storage and isolation of radioactive waste or spent fuel in a geologic rock unit are being carefully evaluated to ensure that radionuclides from the stored waste or fuel will never appear in the biosphere in amounts that would constitute a hazard to the health and safety of the public. The objective of this report is to quantify and present in graphical form the effects of significant geohydrologic and other performance characteristics that would influence the movement of radionuclides from a storage site in a rock unit to the biosphere.

The effort in this study was focused on transport by groundwater because that is the most likely method of radionuclide escape. Graphs of the major performance characteristics that influence the transport of radionuclides from a repository to the biosphere by groundwater are presented. The major characteristics addressed are radioactive decay, leach rate, hydraulic conductivity, porosity, groundwater gradient, hydrodynamic dispersion, ion exchange, and distance to the biosphere. These major performance characteristics are combined with each other and with the results of certain other combinations and presented in graphical form to provide the interrelationships of values measured during field studies. The graphical form of presentation should be useful in the screening process of site selection. An appendix illustrates the use of these graphs to assess the suitability of a site.

FOREWORD

As a result of the operation of nuclear reactors for both commercial power and military material production purposes, radioactive waste is produced that requires isolation from man's environment for many centuries. One possibility for isolating this waste is to place it in permanent storage in the geologic environment. This waste may be in the form of unreprocessed fuel elements, or it may be in the form of a solidified waste product made after the useful energy-containing elements have been reclaimed from the fuel.

Demonstrating the safety of placing either form of waste in the geologic environment is one of the goals of the National Waste Terminal Storage Program. This program is supported by the U.S. Department of Energy. From 1976 to 1978, this program was managed by Union Carbide Corporation-Nuclear Division, Office of Waste Isolation, at Oak Ridge, Tennessee. Starting in July 1978, the management was transferred to Battelle Laboratories, Office of Nuclear Waste Isolation, at Columbus, Ohio. The Savannah River Laboratory is responsible for several studies within this program, one of which is titled, "Parametric Study of Geohydrologic Performance Characteristics for Geologic Waste Repositories."

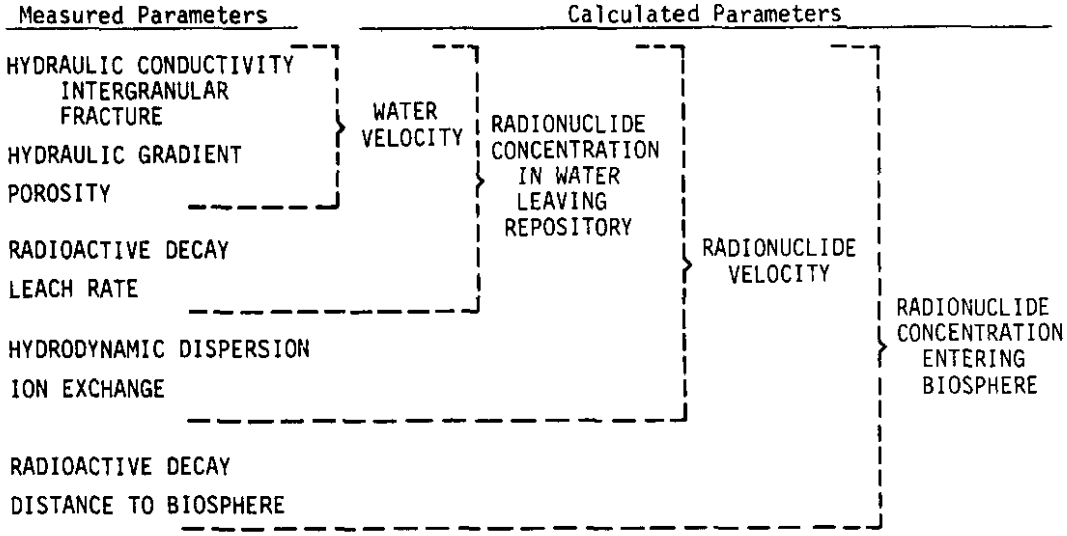
A suitable site for geologic storage of waste can be located only after the performance characteristics expected of it are defined. Most geologists and geological engineers have an intuitive concept of what constitutes desirable properties and undesirable properties of a geologic site; however, reliance on these poorly defined concepts may cause delay in final acceptance of a proposed site.

Designating criteria for siting a nuclear repository poses a dilemma: (1) if the criteria are general enough to be universally applicable, they are interesting conceptually but of little use in specific applications; or (2) if the criteria are quantitively specific, they are applicable only to a designated rock type and geohydrologic system at a particular location. This dilemma, of course, arises because the host rock is only one part of the total containment system. Thus, criteria should be given, not in terms of specific properties like thickness or hydraulic conductivity, but in terms of the potential for radionuclides to appear in the biosphere. However, such an ultimate criteria as this must be transposed into measurable characteristics to evaluate a specific site quantitatively.

The purpose of this report is to present information that will aid in determing site specifications after ultimate criteria have been defined. This report deals only with geohydrologic characteristics and not with the total development of site specifications, such as engineering rock properties, thermal properties, waste-rock interactions, or socioeconomic parameters. Although these other factors cannot be neglected, the leaching of the waste and transport of the leached radionuclides by groundwater, the subject of this study, is of paramount importance.

In any site investigation, certain geohydrologic parameters will be measured, but it is not always obvious what these parameters mean in terms of the ultimate criteria. However, the meaning of these measured values can be established beforehand by studying the relationship of these parameters over a wide range of possible values. The relationship of the geohydrologic parameters governing the transport of radionuclides is outlined below.

Relationships of Geohydrologic Parameters
to Transport of Radionuclides



One possible method of relating these parameters where many interrelating factors are involved is to develop a computer program to make the complete calculations. However, the assumptions involved in the calculations are sometimes not as clear and evident as when these same calculations are presented in graphical form. Because technical persons other than geohydrologists may have to make judgments on the safety of the geohydrologic system, the graphical form of presentation is used in this report. The graphical method, of course, is confined to analysis of one-dimensional flow. Thus, this method is not a replacement for quantitative computer modeling of the geohydrologic system, but may provide an appreciation of the methods and assumptions involved.

The text discusses the development of the graphs. These graphs are presented following the text. The Appendix at the end of this report presents an example of the use of this information for a specific situation, so that the reader may follow the use of the graphs for evaluating a site.

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PARAMETRIC STUDY OF GEOHYDROLOGIC PERFORMANCE CHARACTERISTICS FOR GEOLOGIC WASTE REPOSITORIES

INTRODUCTION

One of the major objectives of the National Waste Terminal Storage Program is to identify potential geologic sites for storage and isolation of radioactive waste (and possibly irradiated fuel), and to develop repositories at the most suitable sites.

The purpose of this report is to assemble and present geohydrologic relationships in a convenient form that will be useful in the evaluation of potential storage sites for radioactive waste in geologic media. This report is essentially a workbook consisting of graphs accompanied by necessary explanatory text.

Many of the calculations required to generate the graphs presented in this report were made using a desk calculator. However, a one-dimensional computer code was used to generate the information on the effect of diffusion and dispersion on the movement of radioisotopes traveling with groundwater.

Transport by groundwater is by far the dominant mechanism by which radionuclides can be moved out of a geologic repository. Therefore, this report presents information to allow this transport to be estimated for a potential site, once the various parameters for the site (e.g., hydraulic gradient, hydraulic conductivity, porosity, exchange coefficients, and dispersivity) have been determined.

RADIOACTIVE DECAY AND STORAGE TIME

The aim of terminal storage of radioactive waste is to isolate the waste from man's environment until release of the waste would no longer be a hazard to health and safety. This is possible because the major hazard of the waste is the radiation produced as the radionuclides decay. Isolation of the waste until the radionuclides have decayed to a very small fraction of their original value will eliminate the hazard.

Radioactive decay of a nuclide is a statistical process that is described by the half-life of the radionuclide. The half-life is the time required for one-half of the original quantity of a radionuclide to decay. After two half-lives, one-fourth of the original amount remains, and after three half-lives, one-eighth of the original amount remains. Figure 1 shows the amount of

radionuclide remaining as a function of time expressed as the number of half-lives. After ten half-lives, about one-thousandth of the original amount remains, and after twenty half-lives, less than one-millionth of the original amount remains.

A wide range of radioactive nuclides with half-lives ranging to over ten million (10^7) years are present in radioactive waste. The fission product isotopes often identified as those of most concern in radioactive waste are ^{90}Sr and ^{137}Cs. The actinide of most concern (if irradiated fuel is disposed of without reprocessing) is ^{239}Pu.[1,2] Strontium-90 and ^{137}Cs have half-lives of about 30 years, and ^{239}Pu has a half-life of about 25,000 years. The amounts of ^{90}Sr and ^{137}Cs will decrease to one-thousandth of their initial amounts in about 300 years, and to less than one-millionth of their initial amounts in about 600 years. The amount of ^{239}Pu will decrease to one-thousandth of its initial amount in about 250,000 years, and to one-millionth of its initial amount in about 500,000 years. Thus, the quantity of ^{90}Sr and ^{137}Cs will decrease to a level where its release would pose little risk to man in several hundred years. However, several hundred thousand years will be required for ^{239}Pu to reach such a level.

IMPORTANT PARAMETERS FOR GROUNDWATER TRANSPORT OF RADIONUCLIDES

The important parameters governing transport of radionuclides by groundwater are:

Intergranular or Fracture Hydraulic Conductivity

Hydraulic Gradient

Porosity

Radioactive Decay

Leach Rate of Radionuclides from the Waste Form

Hydrodynamic Dispersion

Ion Exchange

Distance to Biosphere

As shown in Figure 2, the hydraulic conductivity, hydraulic gradient, and porosity determine the velocity of groundwater. The relationship between these parameters is given by Darcy's Law or the Poiseuille equation. The concentration of radionuclides in water leaving the repository will be determined by the leach rate of the radionuclides from the waste form and the half-lives of the radionuclides, once the waste form is exposed to water.

Radionuclides will move at the same average velocity as the groundwater only if there is no sorption of the radionuclides by the geologic material through which the water is flowing. If a radionuclide is sorbed by the geologic material, the average velocity of the radionuclide will be less than that of the groundwater. This ion exchange effect is described by a distribution coefficient that expresses the ratio of the concentration of the radionuclide in the geologic material to the concentration of the radionuclide in water, assuming the system is in equilibrium.

Hydrodynamic dispersion, a mechanical or convective process, combined with molecular diffusion influences the transport of radionuclides by groundwater. Although the average velocity of the radionuclides is equal to the average velocity of the transporting water (in the absence of sorption), dispersion and diffusion cause a spreading of the radionuclides. When a stable (nondecaying) nuclide is transported (assuming one-dimensional flow), dispersion will cause some of the isotope to reach a given point downstream of the release point earlier than it would in the absence of dispersion. Dispersion would also cause some of the nuclide to reach the downstream point later than if no dispersion occurred. In the case of a release over a short time interval (a pulse release), dispersion would cause a reduction in the peak concentration of the transported nuclide passing a downstream point. Because a stable nuclide does not decay, all of the nuclide released will ultimately pass a given point downstream, with or without dispersion.

When transport of a radionuclide is considered, however, the interaction of radioactive decay with dispersion produces a more complex situation. Because of the exponential nature of radioactive decay, the total quantity of a radionuclide passing a given point downstream of the release point will increase as the dispersivity increases. Therefore, the time at which the maximum concentration is reached at a given downstream point will occur earlier as the dispersivity increases. These points will be illustrated in detail later in this report.

The half-life of a radionuclide and the distance from the source of release to the point where the radionuclide can enter the biosphere are the final factors that determine the concentration of the radionuclide that enters the biosphere as a function of time. For a given set of transport conditions, the quantity of radionuclide released to the biosphere will decrease as the half-life decreases and as the length of the flow path increases.

GROUNDWATER VELOCITY

The rate at which groundwater moves is determined by the hydraulic gradient, hydraulic conductivity (or permeability), and the porosity (void volume fraction) of the geologic medium. The relationship between these parameters is expressed by Darcy's Law:

$$V_D = Q/A = KH \quad (1)$$

or

$$V_t = V_D/p = KH/p \quad (2)$$

where

V_D = Darcy (flux) velocity, d/t^*

V_t = average (pore) water velocity, d/t

Q/A = flow of water per unit area (specific discharge), = d^3t^{-1}/d^2

H = hydraulic gradient, d_{H_2O}/d

K = hydraulic conductivity, d/t

p = porosity (dimensionless)

The Darcy, or flux, velocity gives the flow of water per unit area. If we consider flow of water in a pipe or a river, the flux velocity is equal to the average water velocity. However, when water flows through the pores or fractures in a solid medium, the average water velocity is higher than the flux velocity by a factor equal to the reciprocal of the porosity of the medium, as expressed in Equation 2.

The flow-per-unit-area as a function of hydraulic gradient and hydraulic conductivity is shown (Figure 3) for values of hydraulic conductivity from 10^{-10} to 100 m/day. The range of hydraulic gradient covered is from 10^{-4} to 10 m_{H_2O}/m. In this case, and in all following graphs, a large range is covered for each parameter. Therefore, the evaluation of potential sites can cover any range or combination of ranges of parameters.

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* Dimensions are given as d = length (distance), t = time, and M = mass.

The average water velocity (V_t in Equation 2) for a given flow-per-unit-area is a function of porosity. Figure 4 gives the average water velocity as a function of flow-per-unit-area for porosities ranging from 10^{-5} to 0.5.

Figures 5a through 5f give the average water velocity as a function of hydraulic gradient for porosities of 10^{-4}, 10^{-3}, 0.01, 0.05, 0.10, and for 0.20 to 0.50.

Figures 3 through 5 provide the flow and groundwater velocities for wide ranges of hydraulic conductivity, hydraulic gradient, and porosity. In the analysis of potential geologic storage sites, the groundwater flow path will probably pass through regions with different values of hydraulic gradient, conductivity, and porosity. In such cases, the distance along the flow path from the repository to a point of interest can be divided into a number of segments, and the velocity can be determined for each segment. Thus, this procedure can be used to estimate the travel time for groundwater through a series of regions with different properties.

In Figures 3 through 5, no distinction is made between fracture hydraulic conductivity and intergranular hydraulic conductivity. There is no general theory for deriving the fracture hydraulic conductivity from a knowledge of the fracture characteristics of a medium (width and length of fractures, number of intersections, orientation, etc.). However, the flow of water through a narrow crack can be described.

The flow of a liquid through a narrow crack is given by[3]

$$Q = \frac{2}{3}\left[\frac{(P_o - P_d)\ d_B^{\,3}\ d_w}{\nu d_L}\right] \qquad (3)$$

where

Q = flow, d^3t^{-1}

P_o = pressure at inlet of crack, $Md^{-1}t^{-2}$

P_d = pressure at outlet of crack, $Md^{-1}t^{-2}$

d_B = half-width of crack

d_w = length of crack perpendicular to direction of flow

ν = viscosity of liquid, $Md^{-1}t^{-1}$; [0.0089 g/(cm-sec) for H_2O at 25°C]

d_L = length of crack from inlet to outlet (flow distance through crack)

$$\frac{(P_o - P_d)}{d_L} = \text{hydraulic gradient, } d_{H_2O}d^{-1}$$

The velocity of liquid through the narrow crack as a function of distance from the crack centerline is given by

$$V_X = \left[\frac{(P_o - P_d)}{2\nu\, d_L}\right] [1 - (d_x^2/d_B)] \qquad (4)$$

where

d_X = distance from centerline of crack

The average liquid velocity through the crack, V_a, is 2/3 of the maximum velocity (the velocity at the centerline of the crack, at $d_X = 0$). Figures 6 and 7 show the effect of crack width and hydraulic gradient on the flow and velocity of water through a crack for crack widths from 0.01 to 1000 μm (1 μm = 10^{-6} m).

LEACH RATE OF RADIONUCLIDES FROM THE WASTE FORM

Liquid radioactive waste resulting from reprocessing of nuclear fuel is expected to be incorporated into a solid form (e.g., glass or ceramic) and encapsulated in metal containers before being placed in a geologic repository. If reprocessing of the fuel is not carried out, irradiated fuel assemblies containing the radionuclides (dispersed in solid uranium oxide encased in zirconium) are expected to be placed in metal containers before being placed in a geologic repository. In either case, water will ultimately come into contact with the solid matrix containing the radionuclides unless the geologic repository remains dry.

If water comes into contact with the solid containing the radionuclides, they will be leached, or dissolved, by the water at a rate determined by the leach rate of the solid. The leach rate of a solid is expressed in units of grams of solid leached (or dissolved) per square centimeter of surface area per day [g/(cm^2-day)]. The total mass of *solid* leached in one day is obtained by multiplying the leach rate by the surface area of the solid. The mass of a radionuclide leached in one day is obtained by multiplying the total mass of solid leached by the weight fraction of the radionuclide in the solid, or

$$M_I = W_I \cdot S \cdot \ell \qquad (5)$$

where

M_I = mass of Radionuclide I leached per day, g/day

S = surface area of solid waste form, cm^2

ℓ = leach rate of solid waste form, g/(cm^2-day)

W_I = weight fraction of Radionuclide I in solid, dimensionless

The rate at which a waste form is leached in units of mass-per-unit-time is proportional to the surface area of the waste form, as shown in Equation 5. The leach rate expressed in units of the fraction of the total amount of the waste form leached per unit time is given by

$$F = \frac{S \cdot \ell}{M_S} = \left(\frac{S}{V}\right)\left(\frac{1}{\rho}\right)\ell \qquad (6)$$

where

F = fraction of waste form leached per day, day^{-1}

M_S = mass of solid waste form, g

V = volume of waste form, cm^3

ρ = density of waste form, g/cm^3

As shown in Equation 6, the fraction of the waste form leached per day is proportional to the surface-to-mass ratio of the waste form and to the leach rate. (The fraction is likewise proportional to the surface-to-volume ratio; however, for a given leach rate and surface-to-volume ratio, the fraction leached is inversely proportional to the density of the waste form.) The surface-to-mass ratio is a function of the density of the waste form, and is equal to the surface-to-volume ratio of the waste form divided by the density of the waste form (see Equation 6). The surface-to-volume ratio is dependent only on the size and shape of the waste form. The surface-to-volume ratios of spheres and cylinders are shown in Figure 8 plotted against the radius of the sphere or the length of the cylinder. The surface-to-volume ratio of a cylinder is also dependent on the diameter of the cylinder, so curves are shown for cylinders for a number of values of the ratio of cylinder length to cylinder diameter.

Studies of waste storage have generally indicated that the solidified waste would be stored in cylindrical form, with a diameter of 30 to 60 cm (1 to 2 ft) and a length of $\sim$250 cm (about 8 ft). The surface-to-volume ratio for these cylinders ranges from 0.072 cm^{-1} to 0.138 cm^{-1} for the 2-ft and 1-ft diameters, respectively. The actual surface-to-volume ratios may be higher than these figures indicate due to internal cracking that occurs during cooling of a waste form such as glass. The surface-to-volume ratio decreases as the size of the waste form increases. Thus, for a given amount of material, the fraction

of radionuclides leached per unit time will decrease as the size of the waste form increases.

If a given size waste form is exposed to water, the leach rate will increase with time because of the increase in the surface-to-volume ratio as the size of the waste form decreases due to leaching. The way in which the surface-to-volume ratio (and thus the leach rate) changes as leaching progresses depends on the initial size and shape of the waste form.

The surface-to-volume ratio and surface-to-mass ratio for a sphere are given by

$$(S/V)_{sphere} = 6/D \quad \text{and} \quad (S/M)_{sphere} = 6/D\rho \tag{7}$$

where D is the diameter and ρ is the density.

The surface-to-volume and surface-to-mass ratios for a cylinder are given by

$$(S/V)_{cylinder} = 2/H_{cyl} + 4/D \quad \text{and}$$

$$(S/M)_{cylinder} = [(2/H_{cyl}) + (4/D)]/\rho \tag{8}$$

where

H_{cyl} = length of cylinder

D = diameter of cylinder

ρ = density

The fraction of the waste form leached in one year is shown as a function of leach rate and surface-to-volume ratio in Figure 9a. Figures 9b through 9e show the fraction of the waste form that would be leached in 500, 5000, 50,000, and one million years, respectively. The time to leach all of the waste form is shown in Figure 9f as a function of the leach rate and the surface-to-mass ratio (assumed to remain constant).

As explained earlier, the fraction of the waste form leached is proportional to the surface-to-mass ratio, and the surface-to-mass ratio of any form increases as its size is reduced. In Figures 9a through 9e, the surface-to-mass ratio is assumed to remain constant throughout the period of interest. The effect of the increase in surface-to-mass ratio is modest until more than 50% of the material has been leached. This ratio then becomes more significant (a larger fraction leached) beyond this point. This progressive increase is illustrated in the discussion in the following paragraph. It should be noted that the surface-to-mass ratio for

a waste form of a given size and shape will vary as the density of the waste form varies, while the surface-to-volume ratio will remain the same regardless of the density.

The fraction leached is shown as a function of time and leach rate (Figure 10) for cylindrical waste forms initially 8-ft long with diameters of 1 ft and 2 ft. For these cases, the change in surface-to-volume ratio (S/V), is taken into account. The x-axis is expressed in units of time divided by the waste-form density, so Figure 10 can be used for any assumed waste-form density. The change in S/V as a function of fraction leached is shown in Figure 11. To illustrate the effect of the change in S/V on the fraction leached, the fraction leached for the 2-ft-diameter cylinder is shown (Figure 10, dotted curve) for a leach rate of 10^{-6} g/(cm^2-day). This statement assumes that S/V remains constant at its initial value of 0.0739 cm^{-1}.

If it is assumed that S/V remains constant at its initial value, a comparison of the curves of Figure 10 shows that 18,500 years would be required to leach 50% of the waste form, and 37,000 years would be required to leach all of the waste form (Figure 10). When the change in S/V is taken into account, the times required for 50% and 100% leaching are reduced to 16,500 years and 26,000 years, respectively.

The above discussion shows that the change in surface-to-volume ratio for proposed sizes of waste forms does not significantly change the amount of the waste form leached until half of it has been leached. After half of the waste form has been leached, the rate increases moderately. Therefore, when the waste form is leached beyond 50% in a given time period, the actual amounts leached will be somewhat higher than shown in Figures 9a through 9e because of the increased surface-to-volume ratios. However, this should not be a significant factor in site-scoping studies.

FILL AND FLUSH TIME OF REPOSITORY

Before radionuclides can migrate from the repository, the free volume of the excavated repository must first fill with water and the water pressure equalize with that in the surrounding rock. During the period while this pressure is approaching equilibrium, all gradients are radially inward, and the fluid within the repository will not participate in the regional flow. After equilibrium is established, fluid within the repository will flow with the regional groundwater. The repository flush time and the leach rate will then govern the escape of radionuclides from the repository.

The time to fill a repository will be determined by the free volume of the repository and the water inleakage rate. The rate of water inleakage into a repository after it is closed will depend on many factors, including the permeability of the surrounding rock and the hydraulic gradient. The gradient will depend on how long the facility has been dewatered. It will be necessary to estimate the average water inleakage rate at each site to determine the time required for water to fill the repository. The fill time for a repository with a free volume of one million cubic meters is shown in Figure 12 as a function of water inleakage rate.

The flush time for the repository will be governed by the groundwater flow rate and the orientation of the repository with respect to the direction of groundwater flow. Figure 13 shows a rectangular repository with the long axis at an angle to the direction of groundwater flow. The relative flush time of the repository is shown in Figure 14 as a function of orientation of the long axis of the repository to the direction of groundwater flow and of the length-to-width ratio of the repository. A flush time of unity is assigned to a square repository with the groundwater flow perpendicular to one side of the repository.

Figure 14 also shows that the repository flush time increases as the direction of groundwater flow becomes more nearly parallel to the long axis of the repository. This has no effect on the rate of leaching of radionuclides from the waste, unless the water remains near the waste form long enough so that the concentration of leached material becomes high enough to decrease the leach rate. Ignoring this effect is conservative. However, the smaller the area perpendicular to the groundwater flow direction presented by the repository, the narrower the plume of water containing radionuclides leaving the repository. As the width of the plume narrows, the concentration of radionuclides in the water increases, because the leach rate is assumed to remain unchanged. Thus, if a repository is built with its long axis parallel to the direction of groundwater flow, the plume of water containing radionuclides downstream of the repository will be narrower than if a different orientation had been used, and the radionuclide concentration in the plume will be higher.

HYDRODYNAMIC DISPERSION

Concentration versus Travel Distance Assuming no Dispersion

The concentration of a radionuclide being transported by groundwater will decrease because of radioactive decay. For a constant velocity, this decrease can be expressed as a function of travel distance from the repository if the assumption of no dispersion (or diffusion) is made. The effect of dispersion is discussed in the following section.

Figure 15a shows the decrease in concentration of a radionuclide with distance traveled as a function of the product of the half-life ($T_{\frac{1}{2}}$) of the radionuclide and the velocity (v) of the radionuclide. (The radionuclide velocity may be less than that of the groundwater because of ion exchange. This is described in a following section.) The fact that the relationship between the radionuclide concentration and distance traveled can be expressed as a function of the product of radionuclide half-life and radionuclide velocity shows that the effect of a given increase in one of these parameters can be balanced by a corresponding decrease of the other parameter. For example, the decrease in concentration with distance of a nuclide with a half-life of 100 years and a velocity of 5 meters/year (m/yr) is the same as the decrease with distance of a nuclide with a half-life of 5,000 years and a velocity of 0.1 m/yr.

Figures 15b through 15f also show the decrease in radionuclide concentration with distance traveled as a function of $vT_{\frac{1}{2}}$ out to distances of 0.05, 0.5, 5, 50, and 500 km, respectively. In these figures, the distance traveled is expressed on a linear scale (rather than a log scale as in Figure 15a) to aid in looking at particular distances of interest.

Figures 16a through 16h show the relative radionuclide concentration passing a point of interest versus relative time for half-lives of 1, 10, 30, 10^2, 10^3, 10^4, 25,000, and 10^5 years. In these figures, the relationship is shown as a function of radionuclide velocity because the half-life has been set to a fixed value. The same information is shown in Figures 17a through 17g as a function of half-life for values of radionuclide velocity ranging from 0.0001 to 100 m/yr. Similar figures can be constructed for any half-life or velocity of interest using information from Figure 15.

Effect of Dispersion on Concentration

The concentration of a radionuclide being transported by groundwater, considering steady flow in the X-direction (one-dimensional model), is given by[4,5]

$$\frac{\partial C}{\partial t} = \left(\frac{D}{R_d}\right) \frac{\partial^2 C}{\partial X^2} - \left(\frac{v}{R_d}\right) \frac{\partial C}{\partial X} - \lambda C \qquad (9)$$

where

C = concentration of radionuclide in water, M/d^3

D = hydrodynamic dispersion coefficient, d^2/t

v = velocity of groundwater, d/t

λ = radionuclide decay constant = $\frac{0.693}{T_{\frac{1}{2}}}$

$T_{\frac{1}{2}}$ = radionuclide half-life

$$R_d = \frac{1}{1 + \frac{\rho}{p} K_d}, \text{ dimensionless}$$

ρ = bulk density of geologic material (dry, uncompacted), M/d^3

p = porosity of geologic material, dimensionless

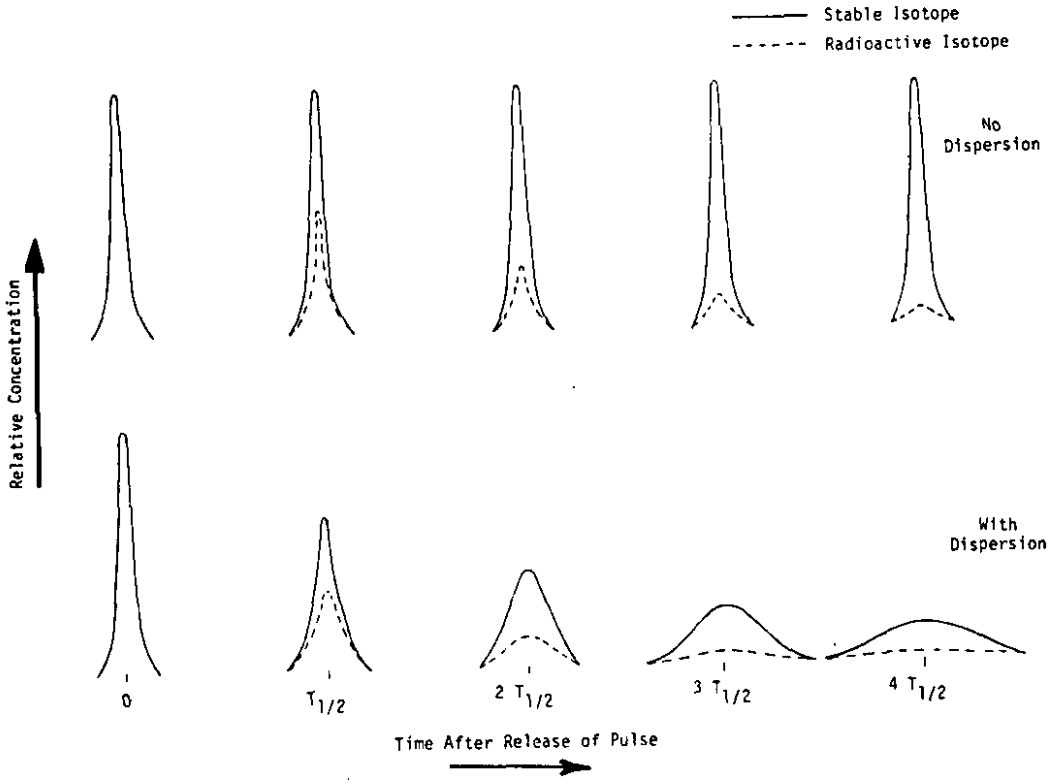
K_d = ion exchange coefficient, (volume of water)/(mass of geologic material) = $d^3 M^{-1}$

The hydrodynamic dispersion coefficient, D, includes the effects of mechanical dispersion and of molecular diffusion.

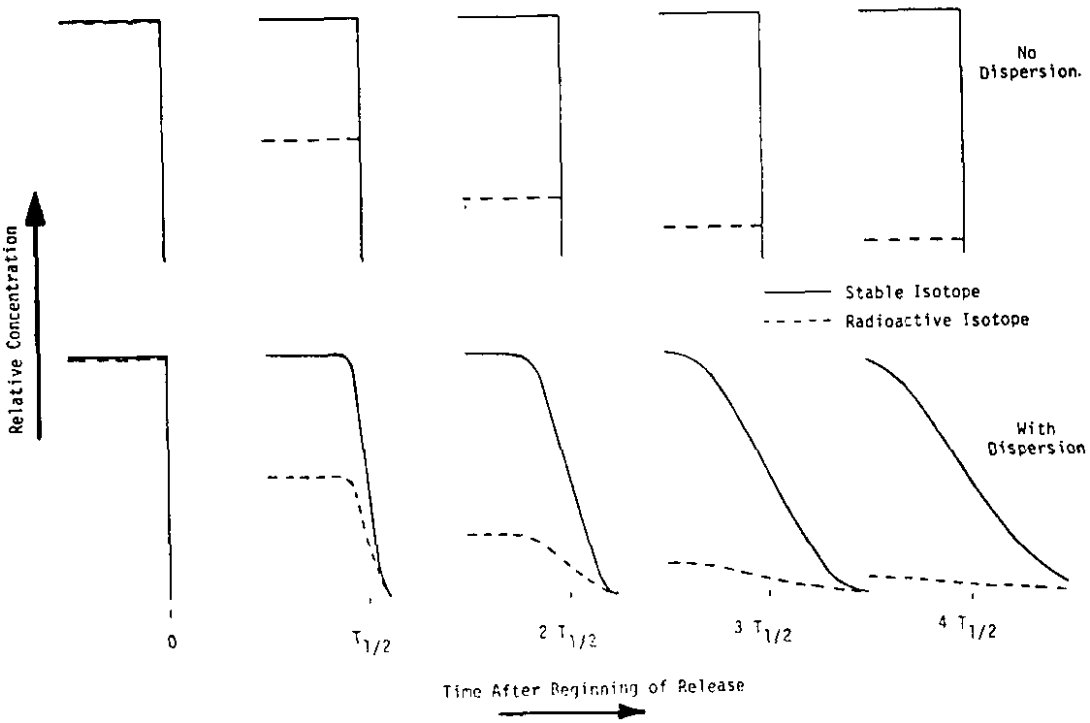
A one-dimensional model was chosen because of the complexity of presenting results (even for a one-dimensional model) and because the results from the one-dimensional model will provide sufficient information to allow comparisons of various potential sites in the selection process. As the number of potential sites is reduced, more detailed multi-dimensional calculations will probably be made by the investigators of the sites, using site-specific values of the significant parameters.

The one-dimensional model overestimates the concentration of radionuclides along the groundwater flow path, and is thus conservative, because dispersion is allowed only in the longitudinal direction. However, because dispersion is not permitted in directions transverse to the direction of groundwater flow, no information on concentration of radionuclides away from the axis of flow is obtained. As stated earlier, the information obtained using the one-dimensional model (and given in this report) is believed to be satisfactory for evaluating sites up to the point when more complex, site-specific calculations will be made by the investigators.

The effect of dispersion and radioactive decay on the transport of radionuclides by groundwater is illustrated by Sketches A and B for pulse injections and for continuous releases, respectively, assuming the source decays with the half-life of the radionuclide.



SKETCH A. Wave Form of Pulse Release with Time (one-dimensional constant velocity flow)



SKETCH B. Wave Form of Continuous Release with Time (one-dimensional constant-velocity flow; decaying source)

The behavior of a pulse injection of radionuclide in a one-dimensional constant velocity stream of groundwater is illustrated in Sketch A. The time (along the abscissa) in units of the radionuclide half-life, is the average travel time of the radionuclide to that point. The continuous curves in Sketch A are for a stable (nondecaying) nuclide and the dashed curves are for a radionuclide.

The upper row of sketches in Sketch A show the concentration at a series of points downstream of the point of injection, assuming no dispersion. In these cases, the pulse shape and magnitude do not change for the stable nuclide. Although the shape remains the same for the radionuclide, the magnitude decreases because of decay.

The lower row of sketches shows the same information assuming dispersion occurs. In this case, spreading of the pulse occurs. Although the width of the pulse increases as the travel distance increases, the area under the continuous curves for the stable nuclide remains the same, because the total amount of nuclide in the groundwater does not change. The area under the dashed curve for the radionuclide at a travel time equal to the radionuclide half-life is 1/2 of the area under the curve for the stable nuclide because in one half-life, 1/2 of the radionuclide decays. After a travel time equal to 4 half-lives, the area under the dashed curve is 1/16 of that under the solid curve.

The behavior for continuous injection of a nuclide is illustrated in Sketch B. The source strength of the radionuclide is assumed to decay at a rate determined by the half-life of the radionuclide. This assumption is made because it more closely represents what would actually happen if material is leached from a solid waste form at a relatively constant rate, as would be expected.

The upper row of sketches in Sketch B shows the concentration fronts for a continuous release of a stable nuclide and a radionuclide into a one-dimensional groundwater stream at times after release of 0, 1, 2, 3, and 4 half-lives, assuming no dispersion. The shape of the concentration front remains that of a square wave because there is no dispersion. However, the magnitude of the concentration front for the radionuclide decreases because of radioactive decay.

The lower row of sketches in Sketch B shows the concentration fronts for a continuous release when dispersion of the nuclides occurs in the groundwater. The initially sharp wave front is smoothed as the nuclides are transported. Again, the concentration of the radionuclide decreases with respect to that of the stable nuclide because of decay.

The standard way to show the effects of hydrodynamic dispersion in a parametric way is to plot the relative concentration of nuclide passing a point at a given distance X from the point of release versus the reduced time, for different values of the dispersion number (D/vX). D is the hydrodynamic dispersion coefficient, v is the radionuclide velocity, and X is the distance from the point of release to an arbitrarily chosen point on the flow path. The reduced time is defined as the time after a pulse release of radionuclide occurs (or the time after the beginning of a continuous release of radionuclide) divided by the average time required for the radionuclide to reach the point X on the travel path, assuming no dispersion. Thus,

$$\text{Reduced time} = \frac{\text{time after release}}{\text{average flow time to point of interest}}$$

Note that the reduced time is dimensionless.

For a stable nuclide, the denominator in the expression for reduced time (i.e., the average flow time to the point of interest) can be left unspecified. Thus, one figure can illustrate all points of interest, and the user can define the average flow time for any given point of interest at the time of use. However, when a radionuclide is considered, the average flow time must be defined in absolute time units in order to construct such a figure. This definition is necessary to allow the decrease in quantity of the radionuclide (because of decay) to be properly accounted for. Thus, for radionuclides, a series of figures are required, each for a defined average flow time from the point of release to the point of interest.

It is emphasized that figures of this type show the concentration of the released material passing a fixed point as a function of time.

The location of a particular point of interest is used with the average velocity to determine the average flow time to the point. This average flow time, then, allows the time after release to be determined for any value of the reduced time. When the figures that will be presented later for radionuclides are used, it may be necessary to interpolate when a particular point is investigated. This is a consequence of the necessity of using actual times (for expressing the average flow time to a point) in the expression for the reduced time.

Effects of Dispersion on Pulse Releases

The results of a one-dimensional analysis for a pulse release of a stable nuclide (including the effects of dispersion) are shown in Figure 18. The release is assumed to occur within a very short time span. Thus, if there were no dispersion, the concentration versus time would be a vertical line one unit high at a reduced time of 1 (i.e., all the released nuclide would be transported to the point at its average velocity).

Figure 18 also shows that a dispersion number (D/vX) of 0.001 causes a decrease of a factor of 100 in the maximum concentration passing the point a distance X from the source relative to the initial concentration in the pulse release. The maximum concentration passing the point is a factor of 1000 lower than the initial concentration in the pulse for a dispersion number of 0.10. Although the maximum concentration passing the point is a factor of 100 or lower compared to the initial concentration in the pulse release for the cases shown, the total amount of material passing the point (i.e., the area under the curve) is the same for all cases, including that with no dispersion. This is true because in this case, the nuclide in the pulse release is stable, so all of the material eventually must pass any given point. It should be noted that as D/vX increases, the time required for all the nuclide to pass the point increases to very large values.

The approach used for stable isotopes cannot be applied in as general a way when a radionuclide is considered, because the decrease in the amount of the radionuclide with time due to radioactive decay must be taken into account. To account for decay, specific times, expressed in units of radionuclide half-lives, are assigned to the flow time for the groundwater from the repository to the point of interest X. A series of curves of concentration passing the point versus reduced time (equal to the time after the pulse release occurs divided by a time equal to a defined number of radionuclide half-lives) as a function of the dispersion number, D/vX, can then be determined for each assumed flow time. Curves of this kind have been prepared for flow times (a factor times the half-life) of the radioisotope from the repository to the point of interest. Factors of 3.322, 6.644, 9.966, 13.288, 16.610, and 19.932 x $T_{\frac{1}{2}}$ were selected because these factors originally present will decrease by factors of 10, 10^2, 10^3, 10^4, 10^5, and 10^6, respectively.

Curves of the type described above are shown for a pulse release in Figures 19a through 19f for values of flow time from the repository to the point of interest (the denominator of the relative time variable plotted on the abscissa) ranging from 3.322 x $T_{\frac{1}{2}}$ to 19.932 x $T_{\frac{1}{2}}$. The concentration passing the point is plotted on the ordinate on a log scale to allow low values of the concentration to be shown. These figures can be used for any nuclide of interest by selecting the proper flow time to the point

of interest (in terms of the half-life of the nuclide) and determining the appropriate range of interest for the dispersion number, D/vX. Times beyond 20 half-lives were not considered because after 20 half-lives, the amount of radioactive material will have decreased to a level so low (one-millionth of its original level) that no significant concern over release of the material to the biosphere will remain.

The effect of radioactive decay is readily seen by inspecting Figures 18 and 19a through 19f. In Figure 18, representing a stable nuclide with no decay, the maximum concentration passing the point is seen to decrease as the dispersion number increases. This is as expected, because as the dispersion increases, the material injected in the pulse release spreads out more. Therefore, the concentration at the peak of the curves decreases as the dispersion increases; while at the same time, a given concentration level will be reached more quickly as the dispersion increases.

Inspection of Figures 19a through 19f, which allow for radioactive decay, shows that the maximum concentration passing the point may increase as the dispersion number increases. This apparently anomalous behavior occurs because of radioactive decay. The shorter time taken for material dispersed in the direction of travel increases the amount of this material reaching the point because of less time for decay. The longer time required for material dispersed in the backward direction decreases the amount of this material reaching the point, because of more time for decay. Because of the exponential nature of radioactive decay, the net effect may increase the quantity of radionuclide passing the point at a given time as the dispersion number increases. This effect becomes more pronounced as the flow time to the point increases. Figure 19f graphically illustrates this effect; the maximum concentration passing the point for a very high dispersion number of 0.1 is over 100 times greater than that passing the point with a dispersion number of 0.01, when the flow time from the point of release to the point of interest is 19.93 x $T_{\frac{1}{2}}$, and occurs much earlier. Figures 20 and 21a through 21f show the same information presented in Figures 18 and 19a through 19f, except that the concentration passing the point is plotted on the ordinate with a linear scale, rather than a log scale.

The total amount of radioactive material that will ultimately pass a given point following a pulse release is also of interest. As mentioned earlier, in the absence of decay, all of the material would ultimately pass the point. Figure 22 shows the fraction of the total quantity of radionuclide released that will ultimately pass a point before it decays (equal to the area under the corresponding curve on Figures 19a through 19f), plotted against the flow time to the point of interest (expressed in units of the nuclide half-life), as a function of the dispersion number, D/vX.

For a pulse release, the information in Figure 22 allows the quantity that will pass any downstream point of interest (before decaying) to be obtained directly, because the quantity released is just the amount in the pulse release. As is explained in a later section, the quantity of radionuclide released in a continuous release can be determined and, when used with the information for a continuous release (Figure 22), can determine the quantity that will pass a given point before decaying.

As shown by Figure 22, the fraction of the radionuclide released that will pass the point before decaying increases with dispersion number. Again, this apparently anomalous behavior is due to the exponential nature of radioactive decay. Figure 23 shows the total amount of material that will pass a point before decaying relative to the amount that would pass the point before decaying with no dispersion ($D/vX = 0$) as a function of radionuclide half-life. This is the same information as that in Figure 22, but is presented in a different form. As shown in Figure 22, the effect of dispersion increases as the distance from the release point increases.

Effect of Dispersion on Continuous Releases

The effect of dispersion on the concentration passing a given point for a continuous release of a stable nuclide (no decay) is shown in Figure 24, where the concentration passing the point is shown versus the reduced time as a function of the dispersion number (D/vX), where D is the dispersivity, v is the velocity, and X is the distance along the flow path from the point of release to the point of interest. As the dispersion increases, the stable nuclide arrives more quickly, but the time at which the concentration reaches the concentration in the source is delayed somewhat.

When a continuous release of a radionuclide is considered, there are two cases of interest. In one case, the concentration of the source decays with the half-life of the radionuclide. In the second case, the concentration in the source is held constant. The first case, with the source decaying, is closer to what would be expected to occur, because the rate at which the radionuclide would be leached from the solidified waste form (after water comes in contact with it) would be relatively constant.

Constant Release Rate

Although the case when the source concentration is constant is of lesser interest, it is discussed first for clarity. As was discussed in the previous section on pulse releases, it is necessary

to express the reduced time (shown along the abscissa) in terms of the radionuclide half-life to generalize the results. Figures 25a through 25f show the concentration passing points with travel times from the point of release of 3.32 x $T_{\frac{1}{2}}$ to 19.91 x $T_{\frac{1}{2}}$ (with steps of 3.32 x $T_{\frac{1}{2}}$) as a function of dispersion number, D/vX. The concentration passing the point is plotted against reduced time.

Figures 24 and 25a through 25f are plotted using a log scale for the ordinate. For a dispersivity of 0 (D/vX = 0), the concentration passing the point remains 0 until the material arrives at the measuring point (a relative time of 1). At this time, the concentration increases abruptly and remains at that level thereafter. When dispersion occurs (D/vX > 0), the radionuclide reaches the point of interest more quickly because of spreading caused by dispersion. However, the fact that the equilibrium concentration increases as the dispersion increases is due to the effects of dispersion and radioactive decay as the radionuclide travels from the point of release to the point of interest.

As discussed in the preceding section on pulse releases, the exponential nature of radioactive decay (half of the radionuclide decays in one half-life) interacts with the effects of dispersion to cause the total quantity of radionuclide passing a given point to increase as the dispersion number increases. An increase in dispersion causes some of the radionuclide to reach the point more quickly and some to reach the point more slowly. However, the total quantity of radionuclide passing the point increases because of decay. The increase in that portion of the radionuclide that reaches the point more quickly (because of a shorter time for decay) is greater than the decrease in that portion of the radionuclide that reaches the point more slowly (because of a longer time for decay). Thus, the constant level reached (after the continuous release with a constant release rate begins) increases as the dispersion number increases.

Figures 26 and 27a through 27f show the same information as shown in Figures 24 and 25a through 25f, except that the concentration passing the point, shown on the ordinate, is plotted using a linear scale. This enables determination of radionuclide concentrations passing the point of interest at the higher concentrations more accurately than is possible using the log plots.

Decaying Release Rate

A continuous release with the release rate decaying with the same half-life as that of the radionuclide is a more realistic situation than a continuous release with a constant release rate because the leach rate of a solid waste form in contact with water would be expected to be relatively constant (leaching of the solid waste form is discussed in an earlier section). Thus, because of the decay of the radionuclide in the waste form, the release rate of the radionuclide would decrease with a half-life equal to that of the radionuclide.

Figures 28a through 28f show the concentration of radionuclide passing points with average travel times of 3.32 x $T_{\frac{1}{2}}$ to 19.91 x $T_{\frac{1}{2}}$ plotted against reduced time as a function of dispersion number. All of these figures are for a continuous release with a decaying release rate, and correspond to Figures 25a through 25f for a continuous release with a constant release rate.

The early portions of the curves for a continuous release with a decaying release rate (Figures 28a through 28f) are quite similar to the early portions of the curves for a continuous release with a constant release rate (Figures 25a through 25f). This similar behavior occurs because during this time, the radionuclide has decayed for only a short time so the rate of release has decreased only a small amount. Thus, little effect on the concentration is seen. The length of time this agreement persists is roughly equal to the time required for the value of concentration passing the point to reach its maximum value when the continuous release has a decaying source; i.e., about 0.8 of the travel time when the travel time to the point of interest is 3.32 x $T_{\frac{1}{2}}$, decreasing to about 0.4 of the travel time when the travel time is 19.91 x $T_{\frac{1}{2}}$.

After the point of maximum concentration passing a point of interest is reached, the decay of the release rate becomes dominant for a continuous release with a decaying source. This is most clearly seen by considering the curves with no dispersion in Figures 28a through 28f (for a dispersion number, D/vX, of 0). In these cases, the concentration reaches maximum values when the relative time is 1.0. This maximum value is equal to the initial concentration of the release decayed for a time equal to the travel time to the point, since no dispersion occurs in these cases. Beyond this time, the concentration of the radioisotope passing the point decreases at a rate determined by the half-life of the radionuclide (i.e., decreases by 1/2 in one half-life). Similar behavior occurs when dispersion is present; however, in these cases, the higher the dispersion number, the more quickly the decaying release rate becomes dominant. This is most graphically demonstrated by the curve for a dispersion number of 0.10

(Figure 28f), where the decaying release rate becomes dominant after a reduced time of approximately 0.4, or after about 8 half-lives. Although this effect is more pronounced the longer the radionuclide travel time to the point of interest, the maximum concentrations reached at these more distant points are much lower than those reached at points closer to the source because of radioactive decay.

It is of interest that, in the case of a continuous release with a decaying release rate, the effect of dispersion decreases the *maximum* concentration passing a point when the point of interest is relatively close to the source. This is shown by Figure 28a, and to a lesser degree by Figure 28b. (As discussed earlier, the *total* amount of radionuclide passing a given point *increases* in all cases as the dispersion increases.) Figure 28a shows that at a point with a travel time from the source of 3.32 x $T_{\frac{1}{2}}$, the maximum concentration for all values of dispersion (or dispersion number) is less than that with no dispersion. At a point with a travel time twice as long, Figure 28b shows that only at a very large dispersion number, 0.10, does the maximum concentration passing the point exceed the maximum value with no dispersion. Even in this case, the difference is very small. At points with longer travel times from the source, the maximum concentration reached at high dispersion becomes significantly larger than that with no dispersion. When the average travel time to the point is 19.93 x $T_{\frac{1}{2}}$, the maximum concentration reached when the dispersion number is 0.10 is almost 100 times that when no dispersion occurs (a dispersion number of 0.0).

Figures 29a through 29f show the same information as shown in Figures 28a through 28f. However, in Figures 29a through 29f, the concentration passing the point of interest, shown on the ordinate, is plotted on a linear scale to enable more accurate determinations of radionuclide concentrations passing the point of interest at higher concentrations.

Figures 28a through 28f and 29a through 29f provide information to allow evaluation of the effects of hydrodynamic dispersion for selected points of interest with travel times of the radionuclide from the source up to 20 half-lives. After a travel time of 20 half-lives, the concentration of the radionuclide will have decreased by a factor of about one million. Beyond this time, it is judged that little concern with release of the remaining quantity of radionuclide to the biosphere will remain.

Total Quantity of Radionuclide Passing a Point as a Result of a Continuous Release

The total quantity of a continuously released radionuclide that passes a given point before decaying is of interest, in addition to the concentration of the radionuclide in the groundwater passing the point as a function of time.

To determine the quantity of continuously released radionuclide that will pass a point on the flow path before decaying, the quantity released must first be determined. This information can then be used with Figure 22 to determine the quantity of radionuclide that will pass a point on the flow path before decaying.

The total quantity of radionuclide released, A_T, during a continuous release is given by

$$A_T = \int_{t_s}^{t_e} q(t)dt \qquad (10)$$

where

$q(t)$ = the radionuclide release rate, amount released/unit time

t_s = beginning time of release

t_e = ending time of release

For a continuous release with constant release rate, the total amount released is

$$A_T = \int_{t_s}^{t_e} q_c dt = q_c(t_e - t_s) = q_c \Delta t \qquad (11)$$

where

q_c = constant release rate

Δt = duration of the release

For a continuous release with the release rate decaying with a half-life equal to the radionuclide half-life, the total amount of radionuclide released is

$$A_T = \int_{t_s}^{t_e} q_o e^{-\lambda(t-t_s)} dt = -\frac{q_o}{\lambda}\left(e^{-\lambda(t_e-t_s)}\right) \qquad (12)$$

where

$q(t) = q_o e^{-\lambda(t-t_s)}$ = release rate at time t

q_o = initial radionuclide release rate

λ = decay constant of radioisotope = $\frac{0.693}{T_{\frac{1}{2}}}$, t^{-1}

$T_{\frac{1}{2}}$ = half-life of radionuclide, t

If the release is assumed to continue indefinitely ($t_e \rightarrow \infty$), the total amount released is

$$A_T = \frac{q_o}{\lambda}\left(e^{-\infty} - 1\right) = \frac{q_o}{\lambda} = 1.4427 \cdot T_{\frac{1}{2}} \cdot q_o \qquad (13)$$

The total amount of radionuclide released during a continuous release is shown in Figure 30 as a function of the duration of the release expressed in units of the radionuclide half-life. Note that the ordinate is expressed as the total quantity of radionuclide released divided by the radionuclide half-life. Thus, to get the total quantity released for a given duration of release, the value read from the ordinate must be multiplied by the radionuclide half-life. Figure 30 shows that for a continuous release with the release rate decaying with a half-life equal to the radionuclide half-life, the quantity released per unit time decreases, and most of the radionuclide release occurs in a time equal to five half-lives after the release begins.

After the total quantity of radionuclide released has been determined, the total quantity that will pass a given point on the flow path before decaying can be determined by multiplying the total quantity released by the fraction of the radionuclide released that will reach the point of interest before decaying. This fraction can be obtained from Figure 22.

RETARDATION OF RADIONUCLIDE MOVEMENT BY ION EXCHANGE

The distribution of cations between water and the surface of the geologic material is expressed by a distribution (or ion exchange) coefficient, K_d. The distribution coefficient has units of

$$\frac{\text{milliequivalents of exchangeable ion adsorbed/g of geologic material}}{\text{milliequivalents of exchangeable ion in solution/mL of water}}$$

or (mL of water/g of geologic material). (The distribution coefficient may include contributions from processes other than ion exchange. For example, fixation may be of importance for cesium ions). The efficiency of a given geologic medium to retard radionuclide ions is influenced by the cation exchange capacity of the medium, pH of the solution, and the salt (cation) content of the solution. Values of the distribution coefficient may range from 0 (no retardation) to over 1000 mL/g.

The velocity of a cation in terms of the velocity of the groundwater is

$$v_c = \left[\frac{1}{1 + \left(\frac{\rho}{p}\right) K_d}\right] v_\omega = \left[\frac{1}{1 + \alpha K_d}\right] v_\omega \qquad (14)$$

where

v_c = velocity of cation (distance per unit time), dt^{-1}

v_ω = velocity of groundwater, dt^{-1}

ρ = bulk density of geologic material, i.e., density of dry uncompacted material (mass per unit volume), Md^{-3}

p = porosity of geologic material, dimensionless

K_d = distribution coefficient, mL of H_2O/g geologic material

$$\alpha = \frac{\text{mass of geologic material}}{\text{volume of water}} = \frac{\rho}{p}, \quad Md^{-3}$$

Figure 31 shows the ratio of radionuclide velocity to groundwater velocity as a function of the distribution coefficient, K_d, and of α. For K_d values near 0, little reduction of radionuclide velocity occurs, even in materials of low porosity. At higher K_d values, substantial reduction of the radionuclide velocity results.

The ratio of mass of geologic material to volume of H_2O (α) will vary with the density of the geologic material and with the porosity of the material (it is assumed that the geologic material is saturated with water; i.e., all pore space is filled with water). Figures 32a through 32h show the average radionuclide velocity as a function of groundwater velocity and distribution coefficient for values of α ranging from 1 (very high porosity material) to 10,000 (extremely low porosity material).

EFFECT OF DISTANCE TO BIOSPHERE

The importance of the distance that radionuclides leached from waste must travel to reach the biosphere is illustrated throughout the figures presented in this report. It is emphasized that the distance to the biosphere is of particular importance for radionuclides as compared to stable elements (e.g., arsenic or mercury) because of the decay of the radionuclides. If it were not for the decay process, it might be necessary to keep the material from ever entering the biosphere (if possible), or assuring that it would enter the biosphere in such a dilute form that it would not present a significant hazard to the health and safety of the public (again, if possible). It is noted that such requirements are not made for the disposal of stable hazardous materials.

Where the path of nuclide movement crosses several rock types having different groundwater velocities, dispersion characteristics, or ion exchange characteristics, it will be necessary to break the analysis into segments that may then be added together.

The methods and graphs presented in this report should permit an estimate of nuclide concentrations entering the biosphere if the necessary parameters are known or assumed. From that point, a different analysis would be used to convert this concentration to a dose-to-man estimate for the general population.

APPENDIX: Example of Use of This Report for a Hypothetical Geologic Repository Site

A set of parameters for a hypothetical geologic repository site and for a hypothetical waste form has been chosen so that use of the information in this report can be illustrated. The parameters chosen are listed in Table A-1. The geologic medium for the repository site is assumed to be saturated with groundwater. The hydraulic conductivity, porosity, and dispersivity values used are typical of a highly impermeable crystalline rock. The hydraulic gradient is typical of gradients found in many areas. The distance to the biosphere was arbitrarily chosen as 0.2 km, as was the value of 10 g/mL for the distribution coefficient. The two values of radionuclide half-life, 30 yr and 25,000 yr, represent values near those of three radionuclides of interest (^{90}Sr and ^{137}Cs, 28.1 yr and 30.2 yr, respectively; and of ^{239}Pu, 24,400 yr).

TABLE A-1

Parameters Chosen to Characterize a Hypothetical Repository Site and a Hypothetical Waste Form

Site Characteristics	
Hydraulic Conductivity	10^{-6} m/day
Porosity	10^{-3}
Density of Dry, Uncompacted Geologic Medium	2.5 g/cm^3
Hydraulic Gradient	1 m_{H_2O}/km = 10^{-3} m_{H_2O}/m
Characteristic Axial Dispersion Length	10 m
Distance to Biosphere	0.2 km = 200 m
Distribution (Ion-Exchange) Coefficient	10 g/mL
Waste Form Characteristics	
Waste Form Size	Cylinder D = 0.328 m (1 ft); L = 2.62 m (8 ft)
Waste Form Density	3 g/cm^3
Leach Rate	10^{-6} g/cm^2-day
Radionuclide Half-lives	30 yr; 25,000 yr
Repository Characteristics	
Dimensions	400 m x 200 m x 20 m
Free Volume	10^6 m^3
Orientation of Long Axis to Direction of Groundwater Flow	30°
Average Inleakage Rate During Filling with Water	1 m^3/day

FRACTION OF RADIONUCLIDE REMAINING WITH TIME

The fraction of the two radionuclides remaining as a function of time expressed in number of half-lives is shown in Figure 1 of the report. However, because the half-lives in this example are known, a new figure can be constructed in terms of actual time, as shown in Figure A-1. (Numerical figure numbers refer to figures in the main body of this report. Figures in this Appendix will be labeled with the prefix A, i.e., Figure A-1). From Figure 1 and Figure A-1, it is seen that the amount of radionuclide with a half-life of 30 yr decreases to one thousandth of its initial value in approximately 300 yr, and to one millionth of its initial value in approximately 600 yr. For a radionuclide with a half-life of 25,000 yr, the amount decreases to one thousandth of its initial value in approximately 250,000 yr, and to one millionth of its initial value in ∿500,000 yr.

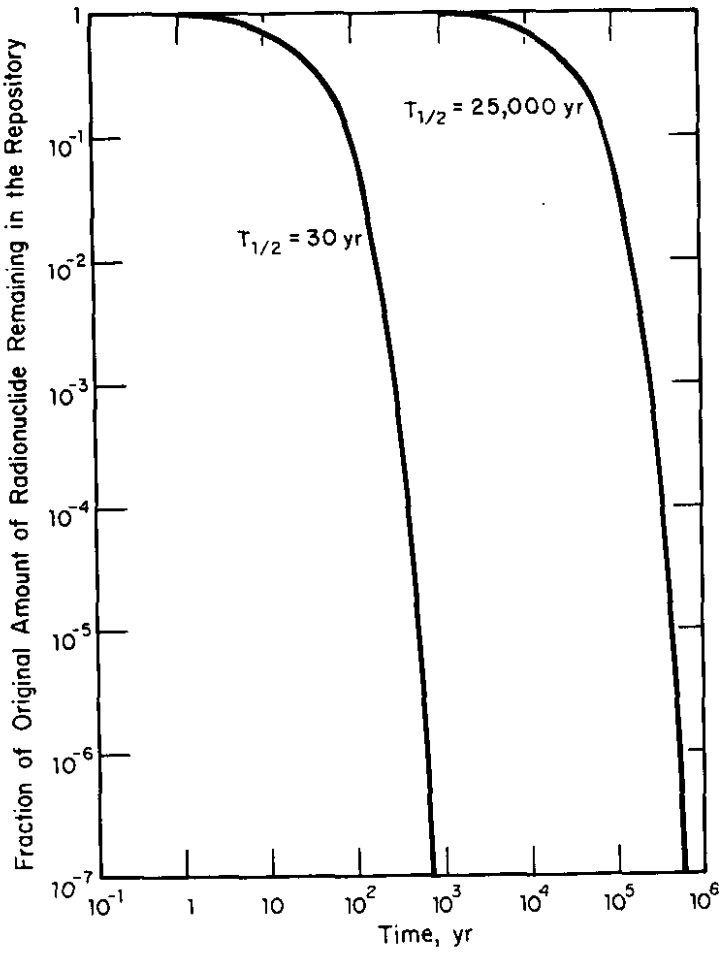


FIGURE A-1. Fraction as a Function of Time of Residual Radionuclides (with half-lives of 30 and 25,000 yr)

FLOW RATE AND GROUNDWATER VELOCITY

The flow, for a hydraulic conductivity of 10^{-6} m/day and a hydraulic gradient of 10^{-3} m_{H_2O}/m, is found to be $\sim 4 \times 10^{-7}$ $(m^3/yr)/m^2$ from Figure 3. The average water velocity, with a porosity of 10^{-3}, is found to be $\sim 4 \times 10^{-4}$ m/yr from Figure 4. Thus, it would require 2500 years for the groundwater to flow one meter through intact rock. From Figures 3, 4, and 5b, the change in flow and water velocity that would result from changes in the values of hydraulic conductivity, hydraulic gradient, and porosity can be readily determined.

FLOW AND VELOCITY OF WATER THROUGH A CRACK

The flow and velocity of water through a postulated crack in the geologic material can be obtained from Figures 6 and 7. For example, for a crack 1 μm wide, with a hydraulic gradient of 10^{-3} m_{H_2O}/m, the flow is $\sim 3 \times 10^{-8}$ (m^3/yr) per meter of crack length and the average water velocity through the crack is ~ 0.03 m/yr. Thus, it would require ~ 33 yr for water to flow one meter through a crack 1 μm wide. (It requires ~ 2500 yr for the water to flow one meter through the intact geologic material, as discussed in the preceding paragraph.)

RATE OF RADIONUCLIDE LEACHING BY GROUNDWATER

Once water comes into contact with the waste form, leaching will begin. The way the waste form is packaged and the geologic environment of the repository will determine how long it will be after the waste is stored before leaching begins. No estimate of this time is made in this example, where consideration is given to the situation once leaching starts.

Figure 8 shows that the surface-to-volume ratio of a cylinder with a radius of 15.2 cm (0.5 ft) and a length of 244 cm (8 ft) [a length-to-diameter ratio of eight] is ~ 0.15 cm^{-1}. Thus, the surface-to-mass ratio (equal to $(S/V)/\rho$, where ρ is the density) is ~ 0.45, assuming a density of 3 g/cm^3. Using this surface-to-mass ratio and the assumed leach rate of 10^{-6} $g/(cm^2\text{-day})$, estimates of the fractions of the waste form that would be leached in 1, 500, and 5,000 yr are found to be $\sim 2 \times 10^{-4}$, ~ 0.09, and ~ 0.9, respectively (Figures 9a through 9d). Because the leach rate is assumed to be linear, ~ 550 yr would be required to leach 10% of the waste form, and ~ 5500 yr to leach 100% of the waste form. As discussed earlier, the amount of radionuclide present in the waste form will decrease with time because of decay.

It is assumed in Figures 9a through 9d that the surface-to-mass ratio of the waste form remains constant. This assumption implies that the leach rate is constant. As discussed in the body of the report, this ratio will actually increase, and thus the leach rate will increase as the waste form becomes smaller due to leaching. Because of this, the time to leach all of the waste forms will be somewhat less than 5500 years.

The effect of the increasing surface-to-mass ratio as leaching proceeds can be determined from information in Figure 10 (since the cylinder is assumed to be 8 ft long and 1 ft in diameter). The time to leach a given fraction is shown (Figure 10) for cylinders 244 cm (8 ft) long with diameters of ∿61 cm (2 ft) and 30.5 cm (1 ft), taking into account the changing surface-to-mass ratio. The times to leach 9% and 90% of a waste form initially 244-cm long and 30.5-cm in diameter with a density of 3 g/cm^3 and a leach rate of 10^{-5} $g/(cm^2\text{-day})$ are found to be ∿500 yr and ∿3900 yr, respectively. These times compare with times of ∿500 yr and 5000 yr assuming a constant surface-to-mass ratio. Thus, the effect is not seen for leaching of 9% of the waste form (as expected), but the difference is seen for leaching of 90% of the waste form (again, as expected). However, the difference at high fractional leachings is not large enough to be of significance in comparative site evaluation studies.

FILL AND FLUSH TIME OF GEOLOGIC REPOSITORY

The free volume in a repository when it is sealed will require time to fill with groundwater, and thus delay the movement of leached radionuclides from the repository. The repository is assumed to be 400 m x 200 m x 20 m, with the long side making a 30° angle with respect to the direction of groundwater flow. This repository is assumed to have a free volume of 160,000 m^3 (the total volume is 1.6×10^6 m^3).

The inleakage rate will need to be individually estimated for each potential site. The average inleakage is assumed in this example to be 1 m^3/day. At this fill rate, it will require ∿440 years to fill the free volume. Even after the free volume is filled, water will not begin to move out of the facility until the hydrostatic pressure in the repository reaches equilibrium with the inleaking water. Only then will groundwater flow through the facility.

The time required for water to traverse the facility is called the flush time. The flush time of the repository depends on the orientation of the repository to the direction of groundwater flow. The area perpendicular to the direction of groundwater flow is (400 sin 30° + 200 cos 30°) x 20, or 7464 m^2. The flow

perpendicular to the direction of groundwater flow was determined earlier to be $\sim 4 \times 10^{-7}$ $(m^3\text{-yr})/m^2$. Thus, the flow rate of water into the repository is 0.003 m^3/yr (or 1.5×10^{-6} gpm). The time to flush the repository free volume of 160,000 m^3, determined from Figure 12 (or by division), is 53 million years. The movement of leached radionuclides out of the repository would thus be delayed for a very long time in the postulated geologic environment.

RELATIVE RADIONUCLIDE CONCENTRATION IN GROUNDWATER WITHOUT DISPERSION

The groundwater velocity in the assumed geologic environment was determined earlier to be $\sim 4 \times 10^{-4}$ m/yr. The product of the assumed radionuclide half-lives, 30 yr and 25,000 yr, and the groundwater velocity (4×10^{-4} m/yr) is 0.012 m and 10 m, respectively. For the radionuclide with a 30-yr half-life ($V \times T_{\frac{1}{2}} = 0.012$), the concentration of radionuclide in groundwater after flowing a distance of 1 meter from the repository is inferred (Figure 15) to be far less than 10^{-6} (actually calculated to be $\sim 10^{-25}$) of the concentration in the groundwater when it left the repository, and thus is of no concern. (One-dimensional flow is assumed throughout the discussion.) The decrease in concentration occurs because of radioactive decay while the groundwater travels the 1 meter distance. The large magnitude of the decrease occurs because of the very slow water velocity, $\sim 4 \times 10^{-4}$ m/yr. (It takes $\sim$2500 yr, or $\sim$80 radionuclide half-lives, for the groundwater to travel 1 meter.)

Figure 15 shows that for the radionuclide with a 25,000-yr half-life ($V \times T_{\frac{1}{2}} = 10$ m), the concentration of radionuclide in the groundwater at 10, 100, and 200 meters from the repository would be ~ 0.5, $\sim 10^{-3}$, and $\sim 10^{-6}$, respectively, of the concentration in the groundwater when it left the repository. It would require $\sim$500,000 yr (20 radionuclide half-lives) for the groundwater to travel 200 meters.

More complete information on the relative radionuclide concentrations versus distance from the point of release (the repository) is shown (Figure 16c) for the radionuclide with a 30-yr half-life, and in Figure 16g for the radionuclide with a 25,000-yr half-life. These figures also show what the effect of a change in groundwater velocity would be on the relative radionuclide concentration downstream of the point of release.

RELATIVE RADIONUCLIDE CONCENTRATION IN GROUNDWATER WITH DISPERSION

The assumed characteristic dispersion length (dispersivity) of the geologic medium is 10 meters. The dispersion coefficient is obtained from

$$D = vd = 4 \times 10^{-4} \text{ m/yr} \cdot 10 \text{ m} = 0.004 \text{ m}^2/\text{yr}$$

where v is the groundwater velocity (determined earlier), and d is the characteristic dispersion length.

The groundwater travel time to a point 200 meters from the repository is ∿500,000 yr. For radioisotopes of half-lives of 30 yr and 25,000 yr, this is equivalent to 16,662 and 20 half-lives, respectively. For the radionuclide with a 30-yr half-life, the travel time is so long as to make further analysis meaningless. Essentially none of this radionuclide would reach the biosphere.

The groundwater travel time of 500,000 yr for a 200-m distance is equivalent to 20 half-lives for the radionuclide with a half-life of 25,000 yr. As determined in the previous section for the situation assuming no dispersion, the concentration of radionuclide would decrease a factor of about one million during this time. Thus, 500,000 yr after the radionuclide appears in the groundwater leaving the repository, it would appear 200 meters downstream of the repository at a concentration of only one-millionth that of the groundwater when it left the repository.

The effects of dispersion on the concentration of radionuclide in groundwater 200 meters from the repository (a travel time equal to 20 radionuclide half-lives) are shown in Figures 19f and 21f for a pulse release, in Figures 25f and 27f for a continuous release with constant release rate, and in Figures 28f and 29f for a continuous release with the release rate decaying at a rate determined by the half-life of the radionuclide. All of these figures are for a point located at the distance downstream of the repository that requires 19.93 radionuclide half-lives for groundwater to travel to the point of interest. For the case under consideration, this distance is 200 meters.

The dispersion number, D/vX, for a point located 200 meters down the flow path from the repository is

$$D/vX = (0.004 \text{ m}^2/\text{yr})/(4 \times 10^{-4} \text{ m/yr} \times 200 \text{ m}) = 0.05$$

This value of the dispersion number is used to choose the appropriate curve from the figures identified above.

All the parameters necessary to interpret the figures of interest are now known:

Distance of point of flow path from repository = 200 m

Flow time from repository = 500,000 yr
= 20 radionuclide half-lives

Dispersion number, D/vX = 0.05

Figure 19f shows the effect of dispersion on a pulse release. The curve for a dispersion number of 0.05 is shown in Figure A-2 with the time axis (abscissa) now labeled in real time, rather than in number of radionuclide half-lives, since the half-life is known. The pulse shape for the case assuming no dispersion is indicated as a dashed vertical line because the width of the pulse is very small.

As shown in Figure 19f, the radionuclide initially reaches the point 200 meters from the repository more quickly the higher the dispersion. In the absence of dispersion, the pulse reaches the point 500,000 yr after release, with a concentration of one-millionth that in the pulse when it left the repository. With a dispersion number of 0.05, a concentration of 10^{-10} that of the original concentration in the pulse is reached at the downstream point 80,000 yr after the release of the pulse. The maximum concentration reached is $\sim 2.5 \times 10^{-7}$ about 250,000 yr after the release, a factor of four less than the maximum concentration assuming no dispersion. After this time, the relative concentration declines reaching a value of 10^{-9} about 500,000 yr after the release of the pulse. The total amounts of radionuclide that passes the point for the various cases is discussed in the following section.

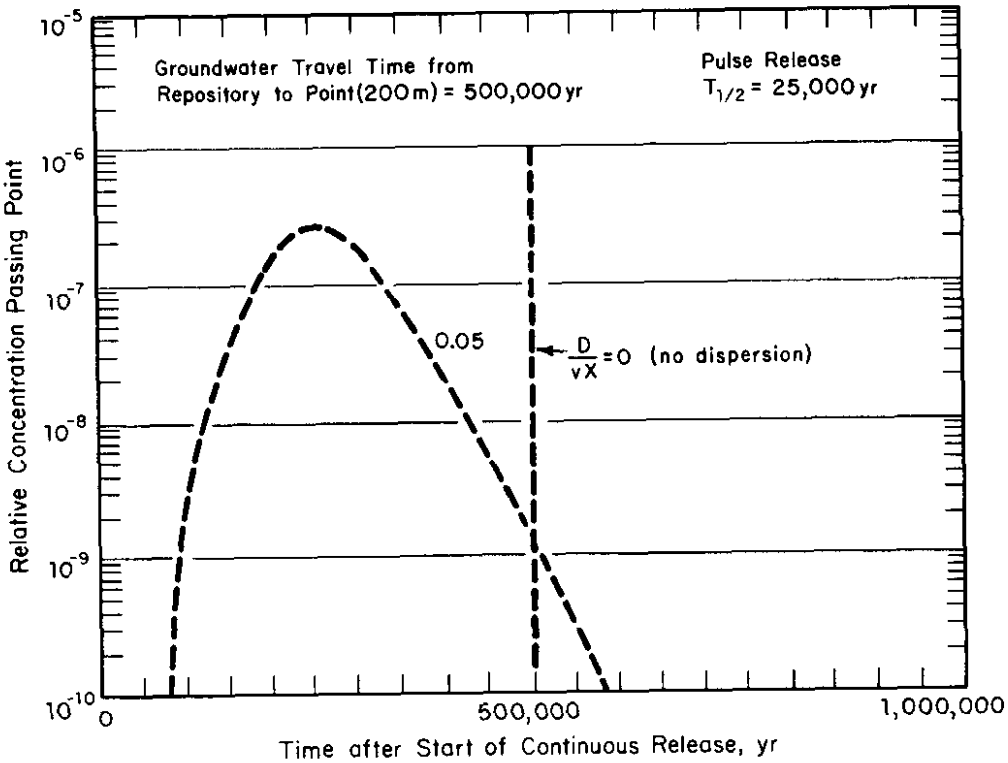


FIGURE A-2. Concentration Relative to Initial Concentration of Radionuclide in Groundwater Passing a Point 200 m Downstream of Repository (pulse release)

The effect of dispersion on a continuous release of radionuclide with a constant release rate is shown in Figures 25f and 27f. The concentration for the case of interest (a dispersion number of 0.05) and the concentration for no dispersion (a dispersion number of 0) relative to the concentration of the source are shown plotted against real time in Figure A-3.

Figure A-3 also shows that with no dispersion, the concentration in the groundwater 200 meters from the repository increases abruptly to 10^{-6} of the concentration in the water leaving the repository 500,000 years after the release begins. The concentration remains at this value thereafter, because the release rate is constant. With a dispersion number of 0.05, the relative concentration of radionuclide reaches 10^{-8} of that in the water leaving the repository about 275,000 yr after the initial release. The relative concentration continues to increase until a value of $\sim 9 \times 10^{-4}$ is reached about one million years after the release begins. The relative concentration remains at this value thereafter.

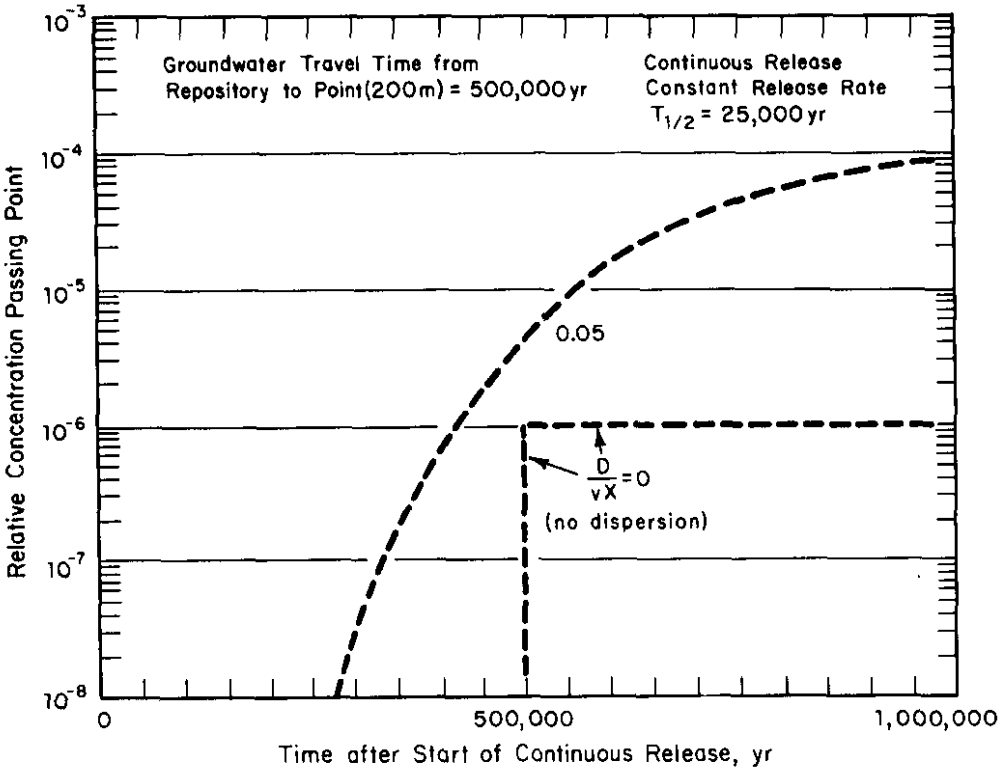


FIGURE A-3. Concentration Relative to Initial Concentration of Radionuclide in Groundwater Passing Point 200 m Downstream of Repository (continuous release; constant release rate)

A case of more interest is that of a continuous release with the release rate decaying with a half-life equal to the half-life of the radionuclide. (This is the situation that would occur if leaching of the waste proceeded at a constant rate, because of decay of the radionuclide in the waste form before it is leached.) Figures 28f and 29f show the effect of dispersion on a continuous release with the source-strength decaying. The relative concentration for a dispersion number of 0.05 and for no dispersion (dispersion number of 0) are shown plotted against real time in Figure A-4.

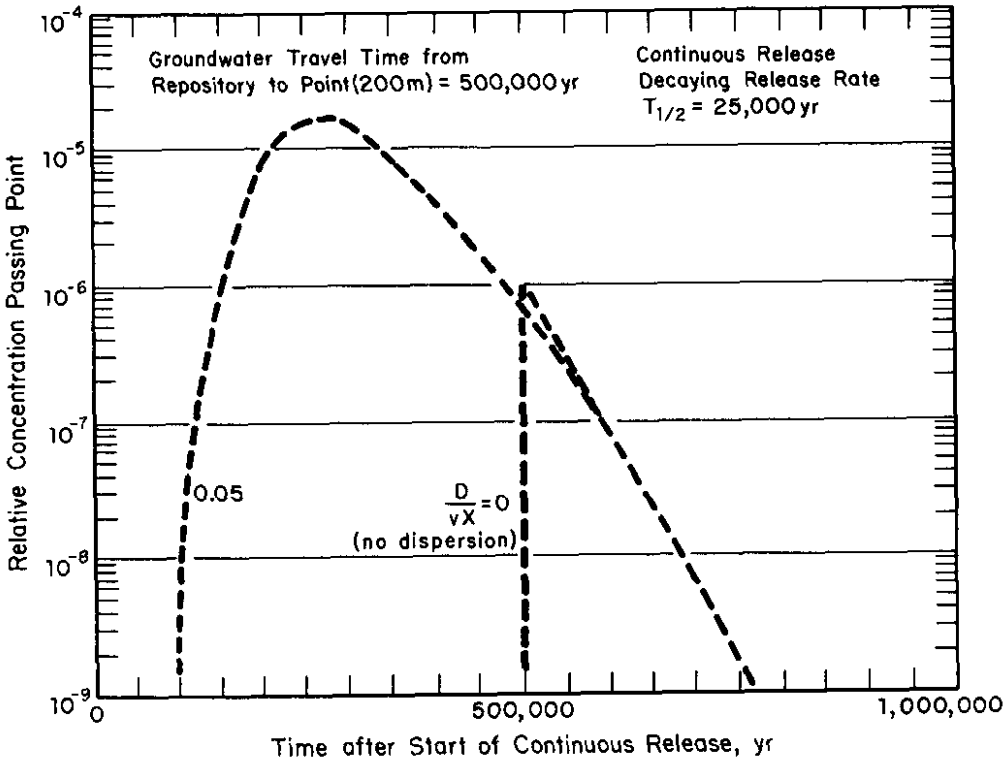


FIGURE A-4. Concentration Relative to Initial Concentration of Radionuclide in Groundwater Passing Point 200 m Downstream of Repository (continuous release; release rate decays with half-life of radionuclide 25,000 yr)

Figure A-4 shows that for the case with no dispersion, the concentration of radionuclide in the groundwater 200 meters from the repository increases abruptly to 10^{-6} of the initial concentration in the groundwater leaving the repository 500,000 yr after the release begins. The relative concentration then decreases with a half-life equal to the radionuclide half-life, because the source strength decays with that half-life. For a dispersion number of 0.05, the relative concentration in the groundwater 200 meters from the repository reaches a value of 10^{-9} about 105,000 yr after the release begins. The relative concentration increases until a value of $\sim 6 \times 10^{-5}$ is reached about 275,000 yr after the release begins. After this time, the relative concentration in the groundwater decreases at a rate approaching the rate of decay of the release rate.

TOTAL QUANTITY OF RADIONUCLIDE REACHING A POINT

The fraction of radionuclide originally present in the waste that will ultimately reach a point 200 meters downstream of the repository can be estimated using information developed on the rate of leaching and on the effects of dispersion.

Leaching of the waste form after the waste form comes into contact with groundwater was estimated to occur at a rate of 0.018% per year in an earlier section of this Appendix. Thus, the initial rate of release of radionuclide would be 0.018% per year of the total present in the waste form. Because of decay of the radionuclide, the amount present in the waste form leached will decrease with time at a rate determined by the half-life of the radionuclide.

As described in the body of this report, the total amount of radionuclide that will be released by leaching all the waste form is equal to (see Equation 12 in report)

$$\frac{q_o}{\lambda}\left[1-e^{-\lambda \Delta t_\ell}\right] = 1.4427\ q_o\ T_{\frac{1}{2}}\left[1-e^{-\lambda \Delta t_\ell}\right]$$

$$= 1.4427\ q_o\ T_{\frac{1}{2}}\left[1-e^{\left(\frac{-0.693}{T_{\frac{1}{2}}}\ \Delta t_\ell\right)}\right]$$

where

q_o = initial radionuclide release rate

$\lambda = 0.693/T_{\frac{1}{2}}$ = decay constant of radionuclide, yr^{-1}

$T_{\frac{1}{2}}$ = half-life of radionuclide, yr

Δt_{ℓ} = time to leach all of waste form, yr
(estimated earlier to be ∿5500 yr)

The calculated amount (before decay) of radionuclide with a 30-yr half-life originally present that is released is

$$q_o \times 1.4427 \times 30 \times \left[1-e^{\left(\frac{-0.693 \times 5500}{30}\right)}\right] =$$

$$= 43.28\ q_o \left[1-e^{-127}\right] = 43.28\ q_o$$

For a radionuclide with a half-life of 25,000 yr, this amount is

$$q_o \times 1.4427 \times 25{,}000 \left[1-e^{\left(\frac{-0.693 \times 5500}{25{,}000}\right)}\right] =$$

$$36{,}068\ q_o \left[1-e^{-0.1525}\right] = 36{,}068\ q_o \cdot [1 - 0.859] = 5101\ q_o$$

The fraction of the radionuclide initially contained in the waste form that is released by leaching before it decays is obtained by dividing the amount that is released before decaying by the amount initially present. In the present case, the amount of radionuclide initially present in the waste form is 5500 q_o, because 5500 years is required to leach the entire waste form, and q_o is the initial radionuclide release rate. The fraction of radionuclide with a 30-yr half-life that is leached (before decaying) is 43.28 q_o/5500 q_o, or 0.0079. The fraction of radionuclide with a 25,000-yr half-life that is leached (before decaying) is 0.927.

The groundwater flow time to a point 200 meters downstream of the repository is 500,000 yr. The radionuclide released from the repository would decay during this travel time. Decay of a radionuclide with a half-life of 30 yr during this long travel time would reduce the amount present to an infinitesimal value (∿10^{-5000} of the quantity originally released), and it is of no concern. The quantity of radionuclide with a half-life of 25,000 yr would decrease to about one-millionth of its initial value during the 500,000 yr travel time. Thus, in the absence of dispersion, the fraction of the radionuclide in the waste form with a half-life of 25,000 yr that would ultimately reach a point 200 meters downstream of the repository is 0.93 x 1 x 10^{-6}, or 9.3 x 10^{-7}. This value is equal to the integral under the curve for no dispersion (D/vX = 0) in Figure A-4. As shown in Figure A-4, it would require ∿500,000 yr for the first of the radionuclide to reach the point of interest; most of the radionuclide would reach this point during the next 100,000 yr.

Dispersion causes the initial quantity of radionuclide to arrive at the point more quickly, and more of the radionuclide will ultimately reach the point. Figure 23 of the report shows that for a dispersion number of 0.05, about 90 times as much of the radionuclide will reach a point with a travel time of 20 radionuclide half-lives, as reaches it when no dispersion occurs. Thus, the fraction of radionuclide that will reach the point 200 meters downstream of the repository with a dispersion number of 0.05 is 90 x 9.3 x 10^{-7}, or $\sim$8 x 10^{-5}. This value is equal to the integral under the curve for a dispersion number of 0.05 in Figure A-4. The first of the radionuclide will reach the point about 110,000 years after the release begins (Figure A-4), and most of the radionuclide will reach the point in the next 300,000 years.

EFFECT OF ION EXCHANGE ON RADIONUCLIDE VELOCITY

The preceding discussion of radionuclide travel time assumed that the radionuclide that is dissolved in groundwater does not interact with the geologic material through which the groundwater flows. However, because of ion exchange, the radionuclide velocity will be less than the groundwater velocity.

The distribution, or ion-exchange, coefficient is assumed to be 10 g/mL. The ratio of grams of dry uncompacted geologic material to milliliters of water, α, is

$$\alpha = \frac{\text{density of geologic material}}{(\text{porosity})(1\ \text{mL/cm}^3)}$$

$$= \frac{2.5\ \text{g/cm}^3}{0.001} = 2500\ \text{g/cm}^3 = 2500\ \text{g/mL}$$

From Figure 31, the ratio of average radionuclide velocity to average groundwater velocity for K_d = 10 mL/g and α = 2500 g/mL is found to be $\sim$5 x 10^{-5}. Thus, the radionuclide would travel much more slowly than the groundwater. The groundwater velocity was determined to be 4 x 10^{-4} m/yr earlier in this Appendix. The average radionuclide velocity would thus be reduced by a factor of a half-million, i.e., from 4 x 10^{-4} m/yr to (4 x 10^{-4} m/yr x 5 x 10^{-5}), or $\sim$2 x 10^{-8} m/yr.

The effect of this large reduction in radionuclide velocity on the quantity of radionuclide that will reach points at various distances from the repository can be estimated by following the procedure given earlier in this Appendix, using a velocity of 2 x 10^{-8} m/yr rather than 4 x 10^{-4} m/yr. However, at this

extremely low velocity, it would require 50 million years for the radionuclide to move 1 meter. This is 2000 half-lives for the radionuclide with a 25,000-yr half-life; therefore, essentially all of the radionuclide would decay during this time. Thus, virtually none of the radionuclide will move more than a very small fraction of a meter from the repository before the nuclide has decayed to an insignificant amount.

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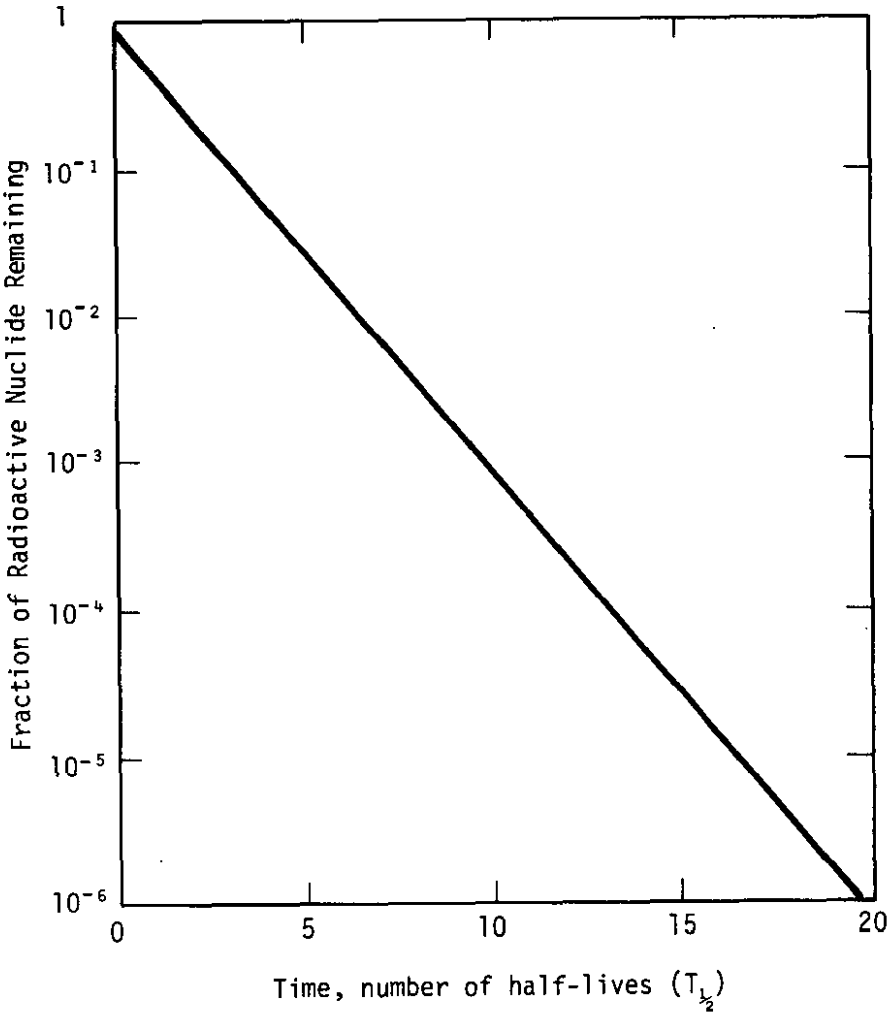

FIGURE 1. Fraction of Radionuclide Remaining as a Function of Time

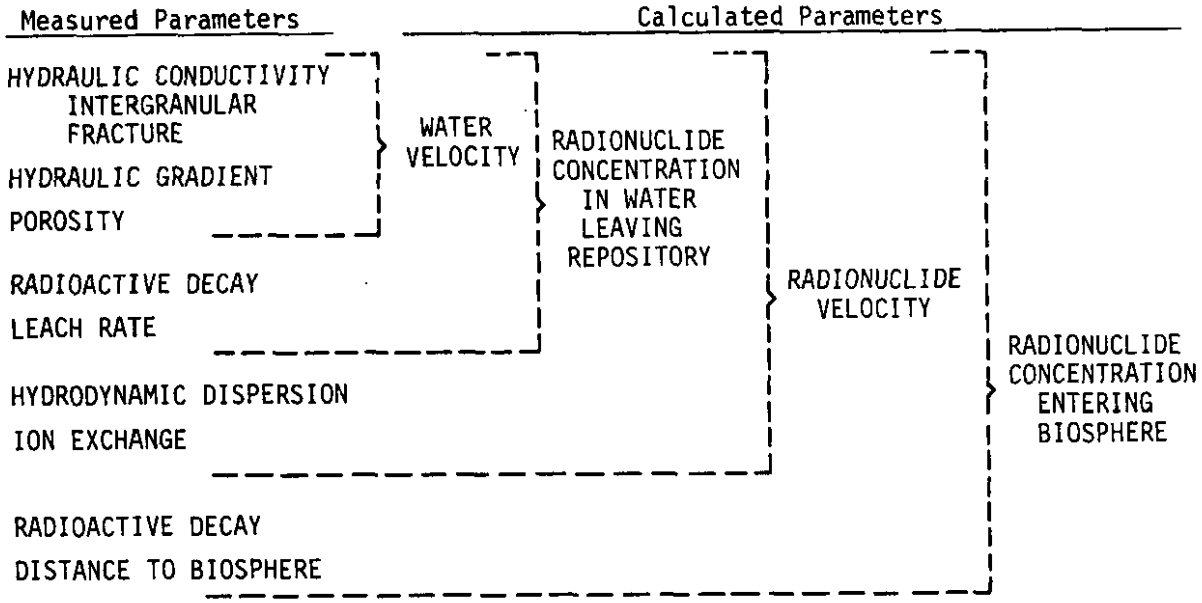

FIGURE 2. Relationships of Geohydrologic Parameters to Transport of Radionuclides

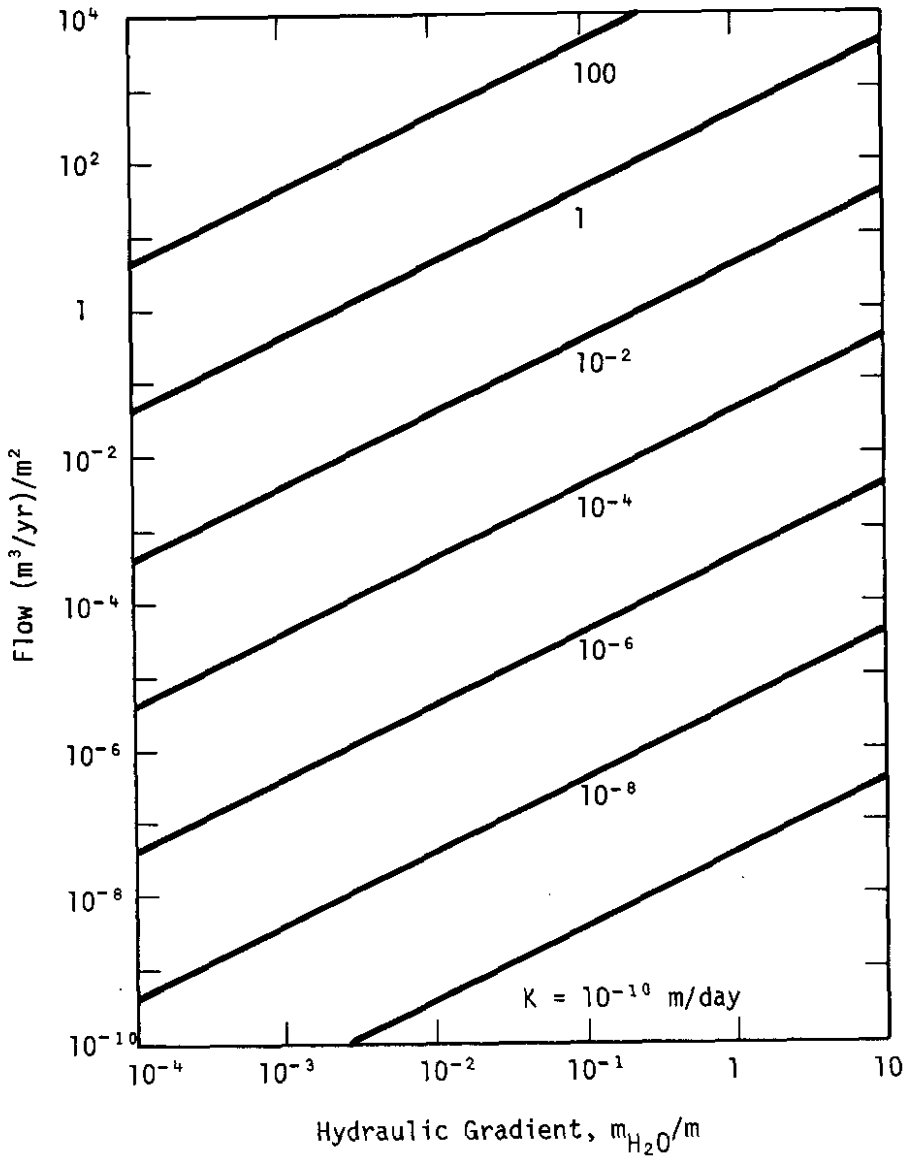

FIGURE 3. Flow as a Function of Hydraulic Gradient and Hydraulic Conductivity

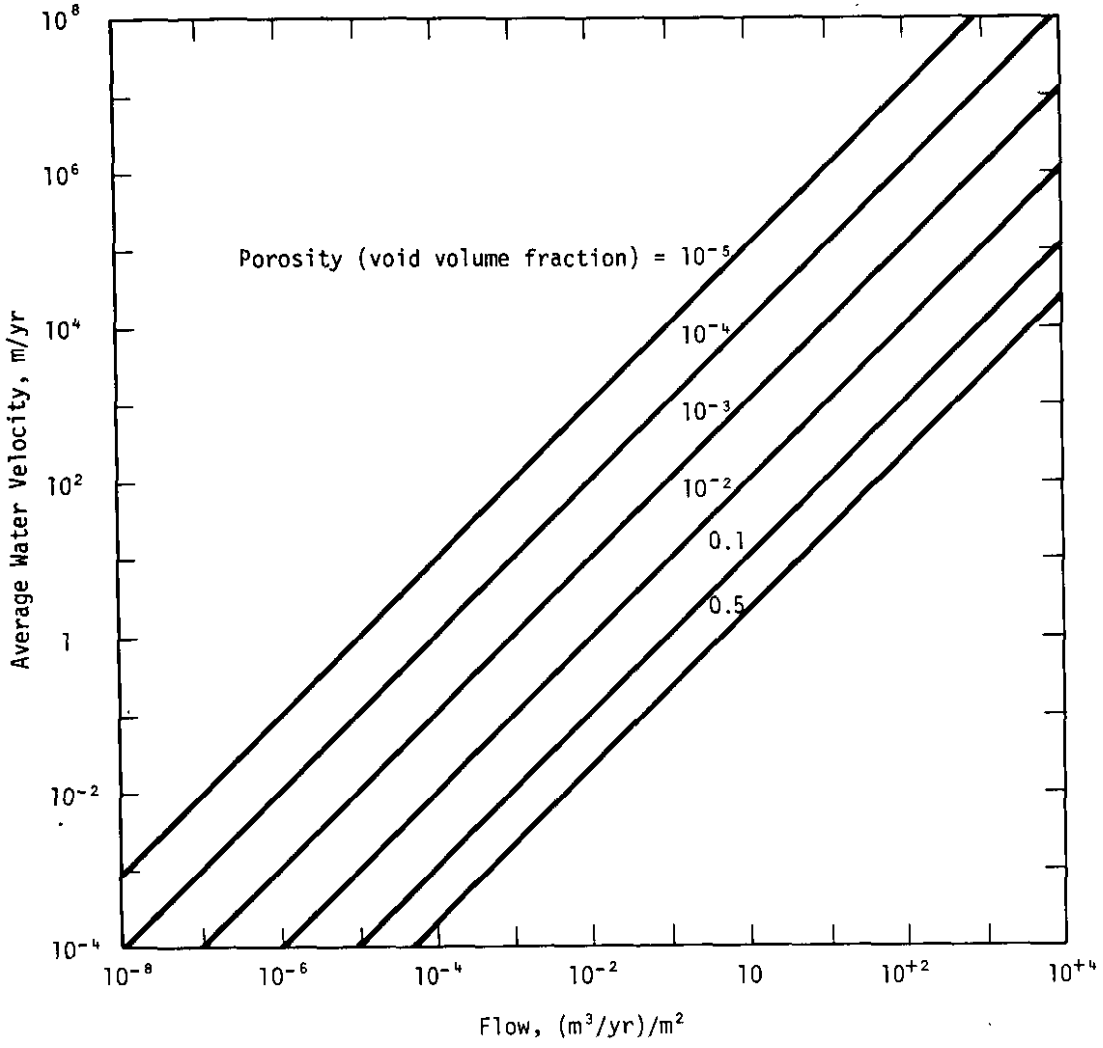

FIGURE 4. Average Water Velocity as a Function of Flow and Porosity

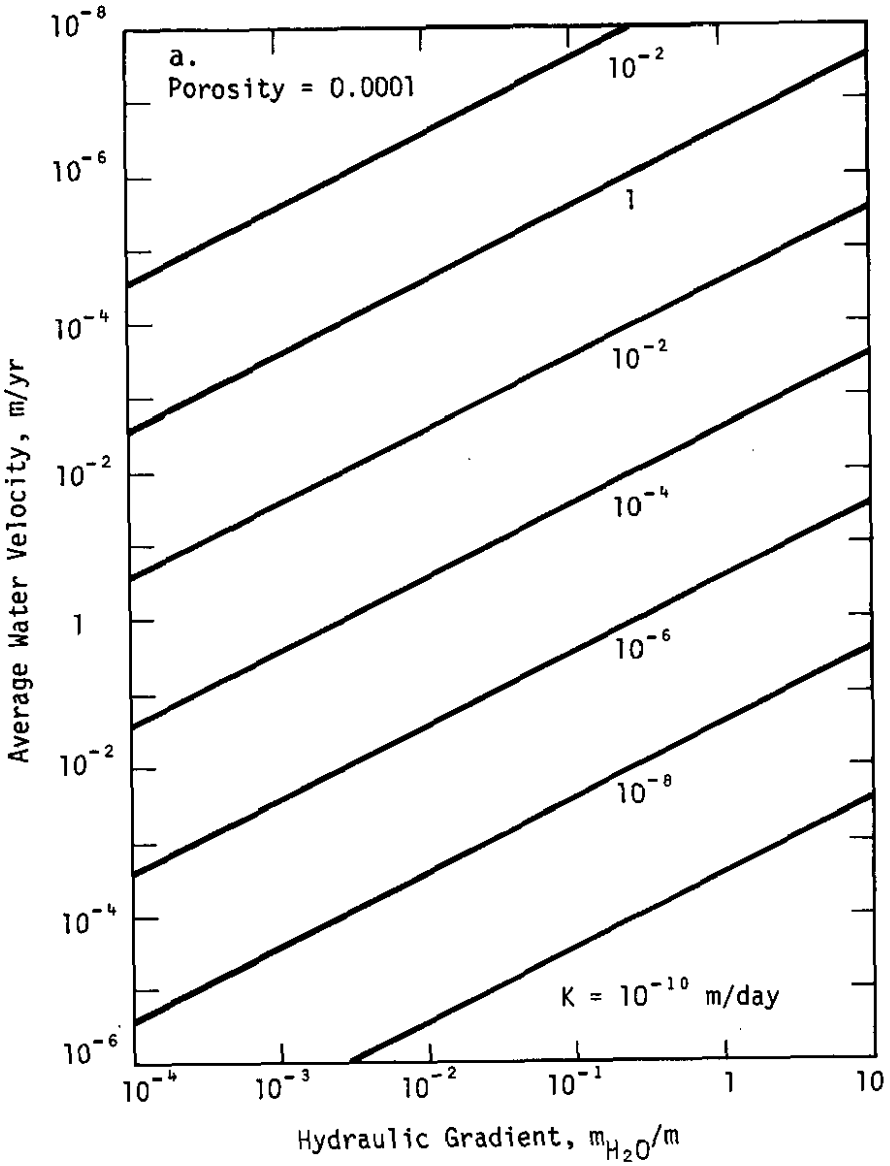

FIGURE 5a. Average Water Velocity as a Function of Hydraulic Gradient and Hydraulic Conductivity (Porosity = 0.0001)

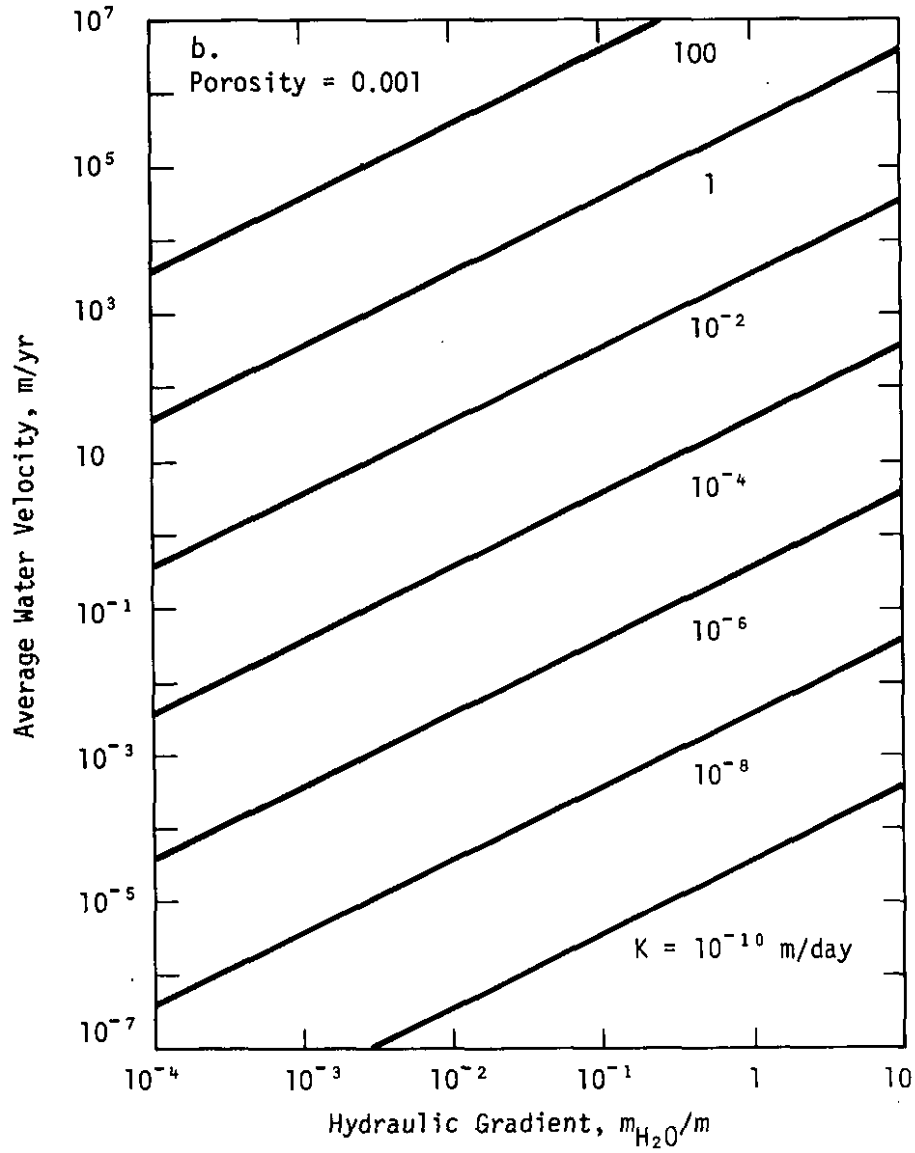

FIGURE 5b. Average Water Velocity as a Function of Hydraulic Gradient and Hydraulic Conductivity (Porosity = 0.001)

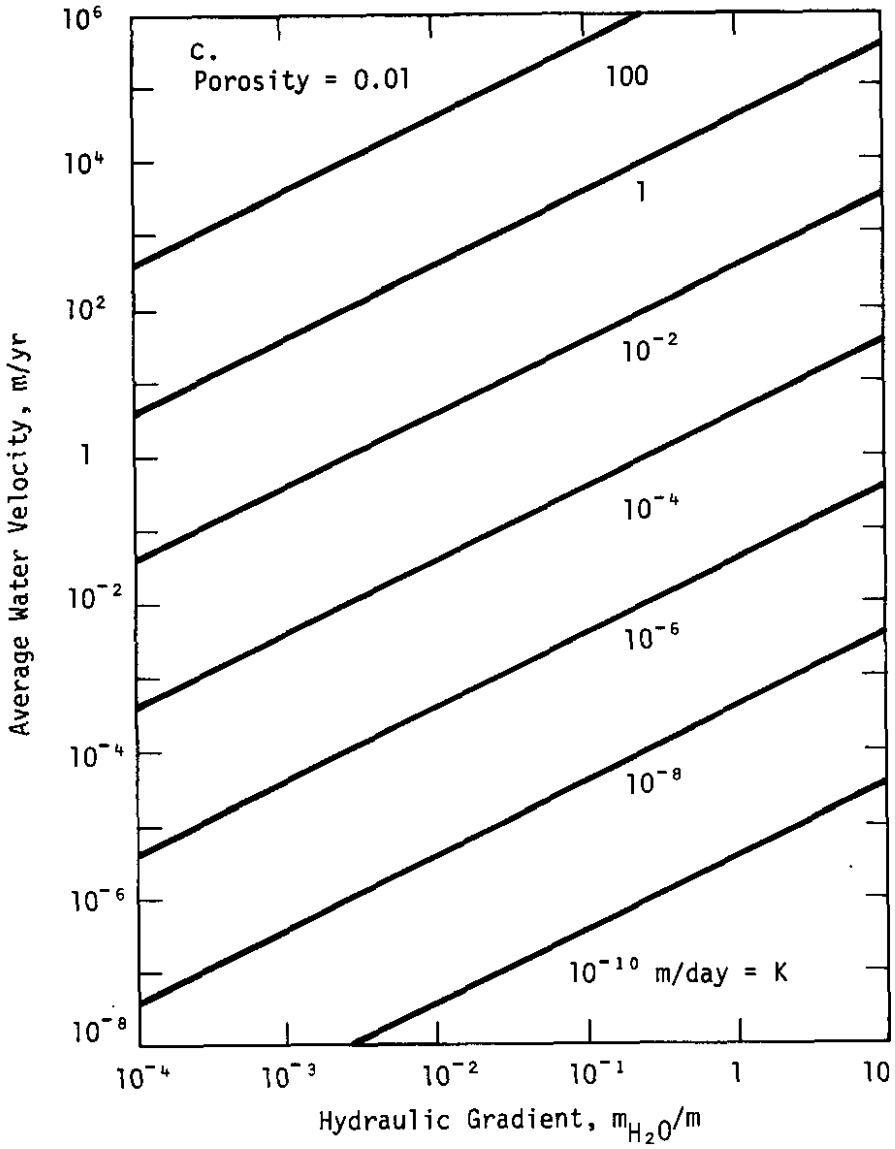

FIGURE 5c. Average Water Velocity as a Function of Hydraulic Gradient and Hydraulic Conductivity (Porosity = 0.01)

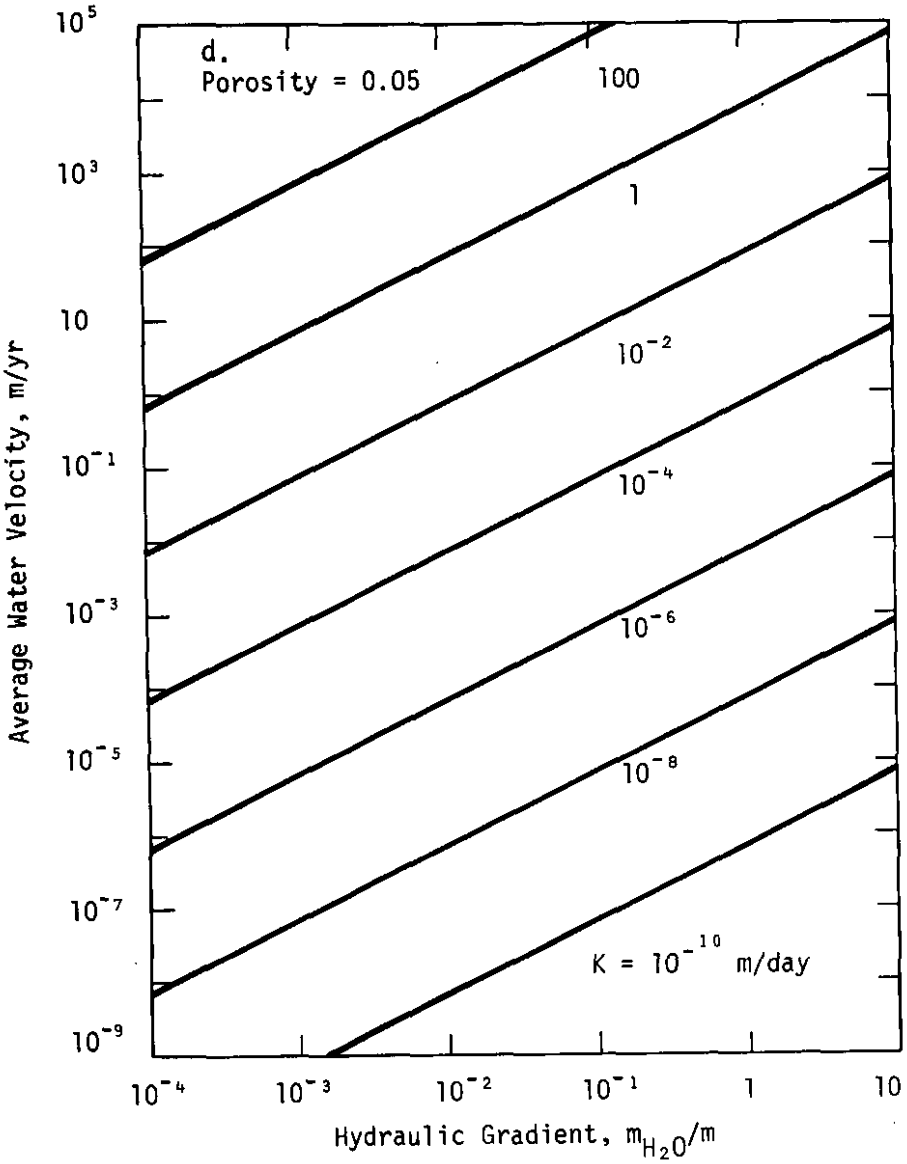

FIGURE 5d. Average Water Velocity as a Function of Hydraulic Gradient and Hydraulic Conductivity (Porosity = 0.05)

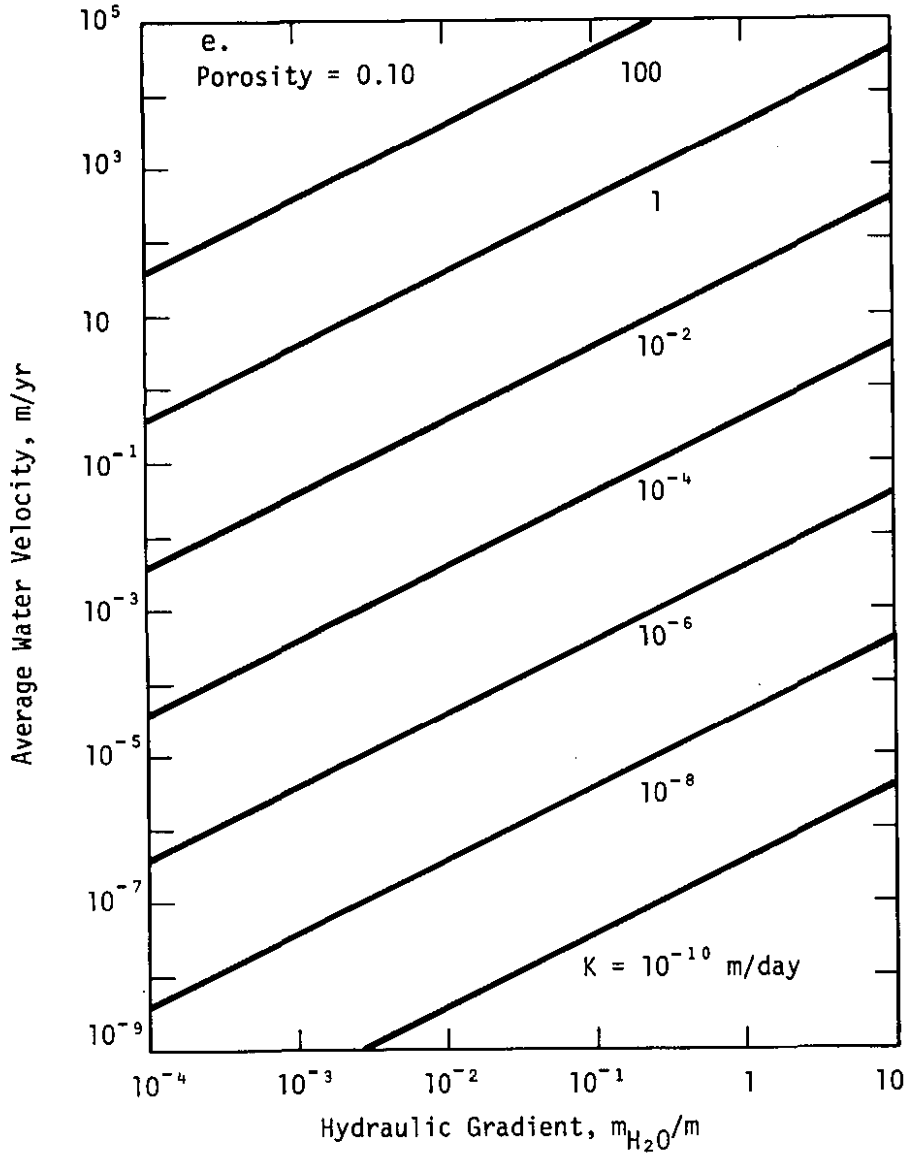

FIGURE 5e. Average Water Velocity as a Function of Hydraulic Gradient and Hydraulic Conductivity (Porosity = 0.10)

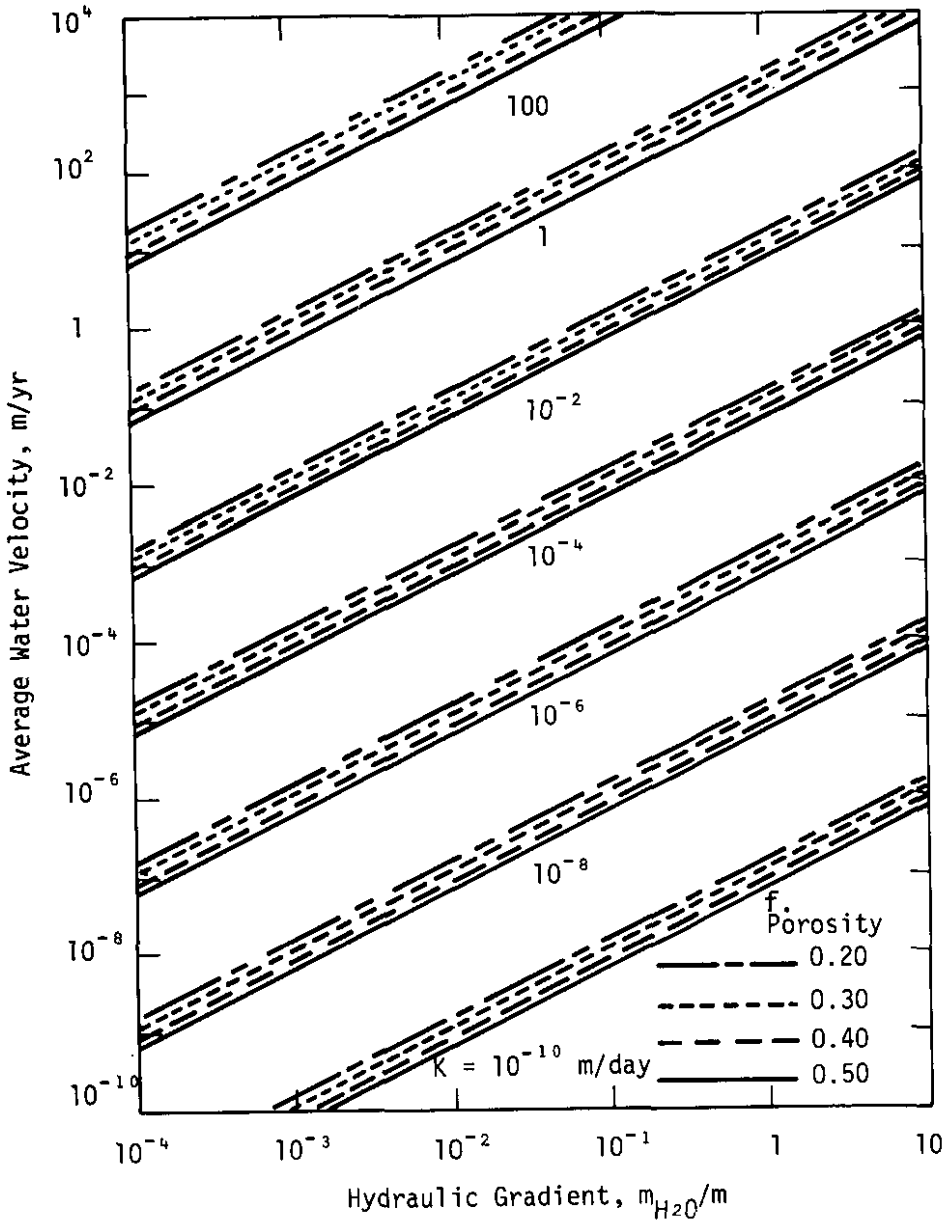

FIGURE 5f. Average Water Velocity as a Function of Hydraulic Gradient and Hydraulic Conductivity (Porosities of 0.20, 0.30, 0.40, and 0.50)

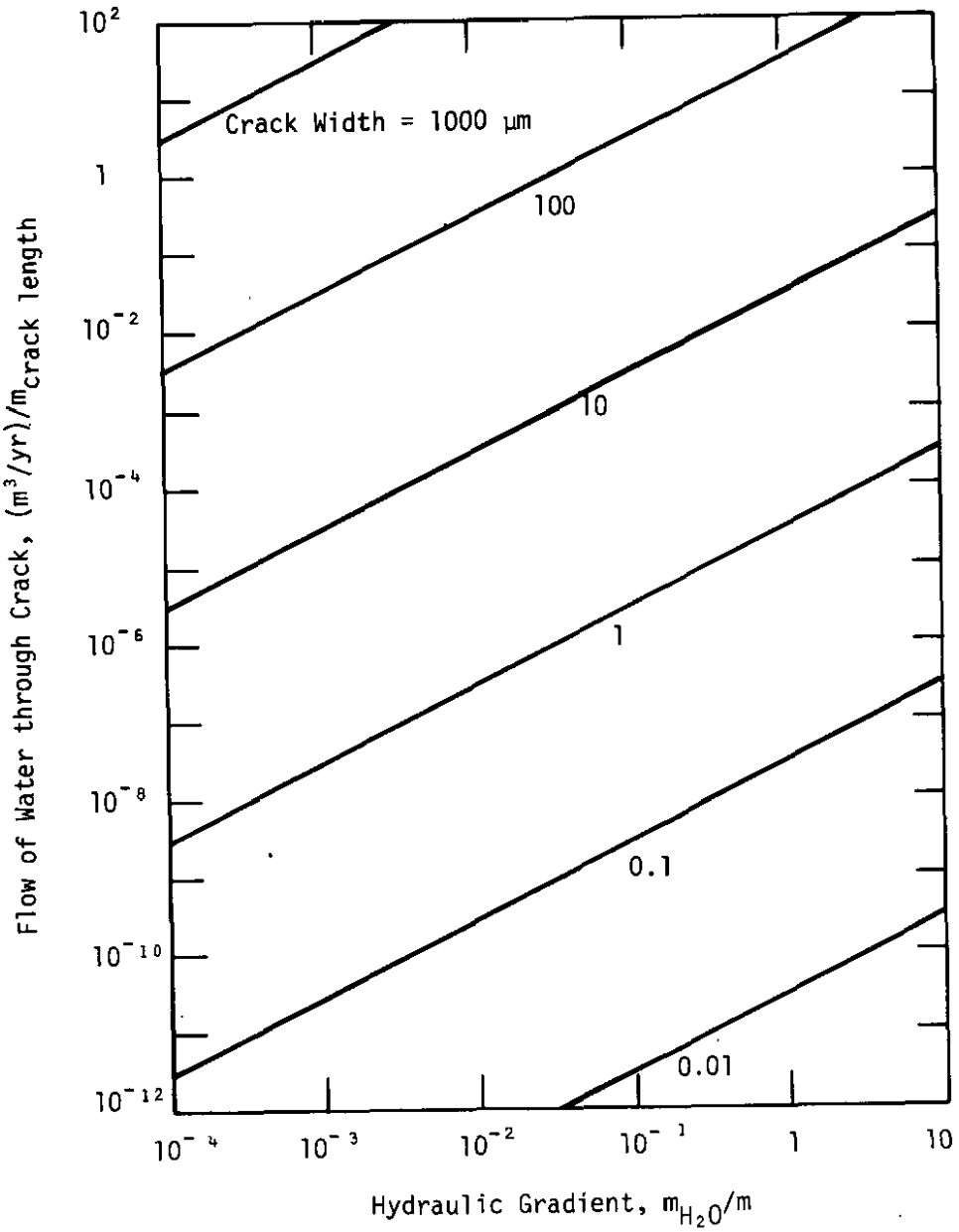

FIGURE 6. Flow of Water Through a Crack as a Function of Hydraulic Gradient (crack widths of 0.01 to 1000 µm)

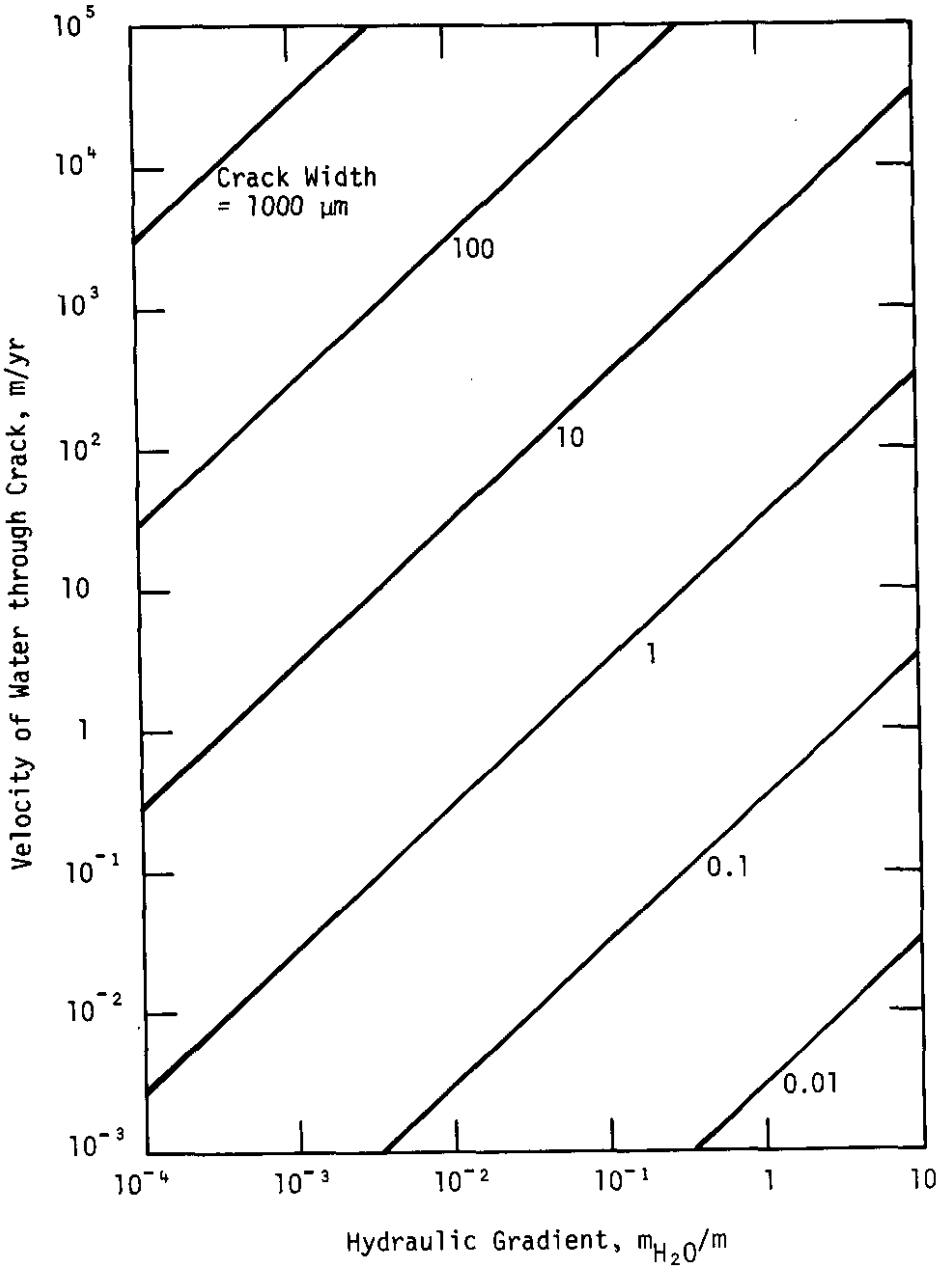

FIGURE 7. Velocity of Water Through a Crack as a Function of Hydraulic Gradient (crack widths of 0.01 to 1000 µm)

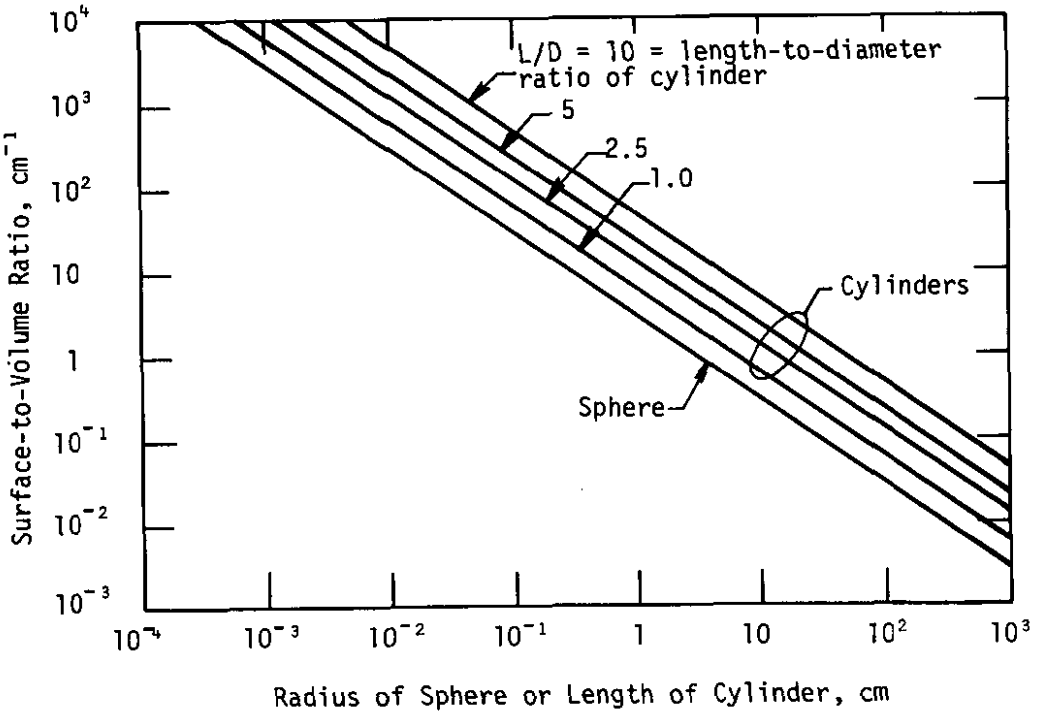

FIGURE 8. Surface-to-Volume Ratios for Spheres and Cylinders

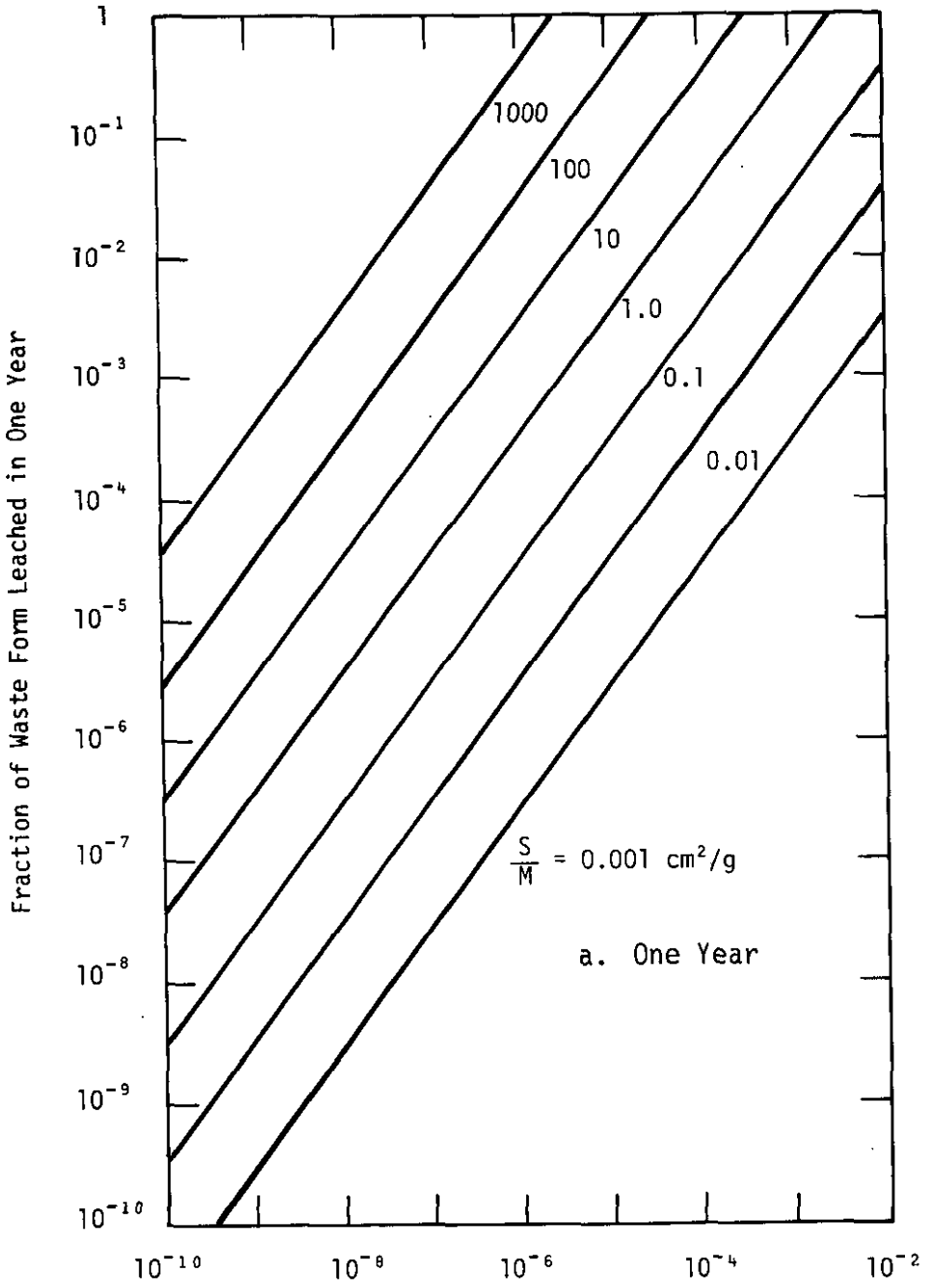

FIGURE 9a. Fraction of Waste Form Leached as a Function of Leach Rate (surface-to-mass ratios of 0.001 to 1000 cm^2/g) and Time (one year)

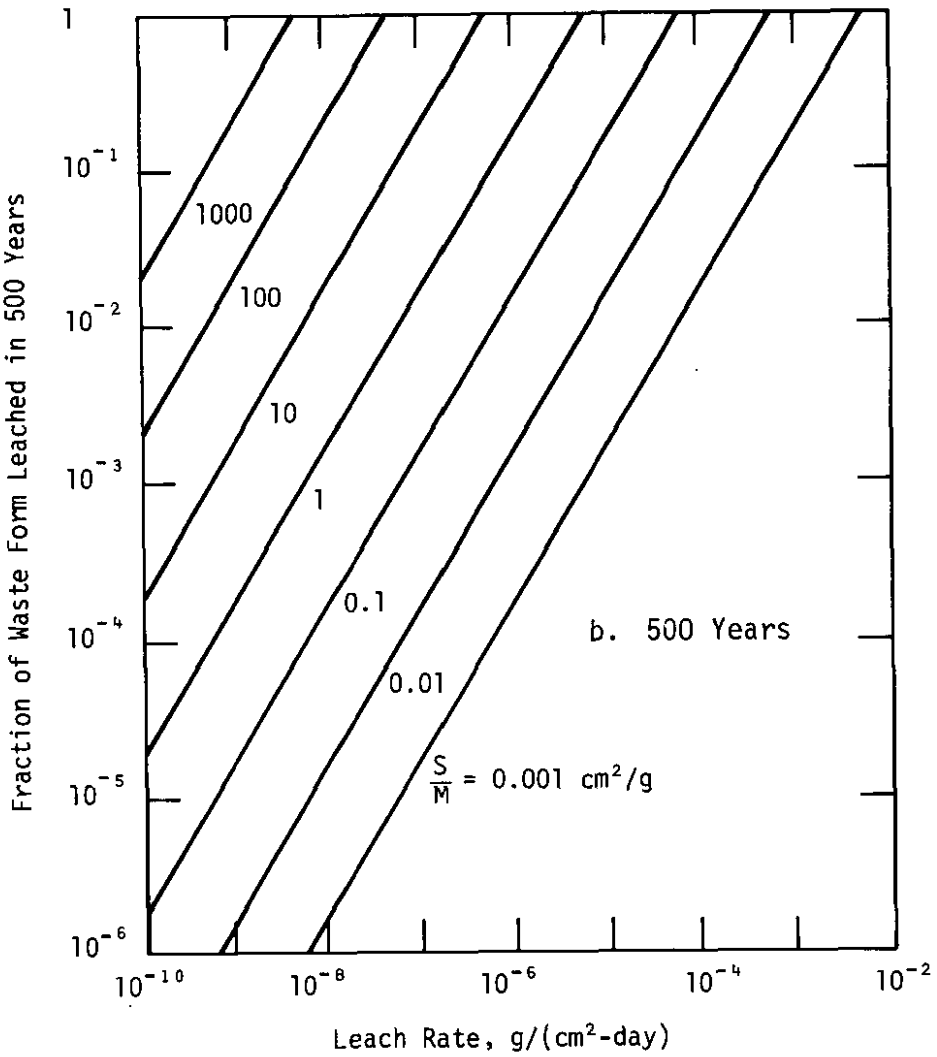

FIGURE 9b. Fraction of Waste Form Leached as a Function of Leach Rate (surface-to-mass ratios of 0.001 to 1000 cm^2/g) and Time (500 years)

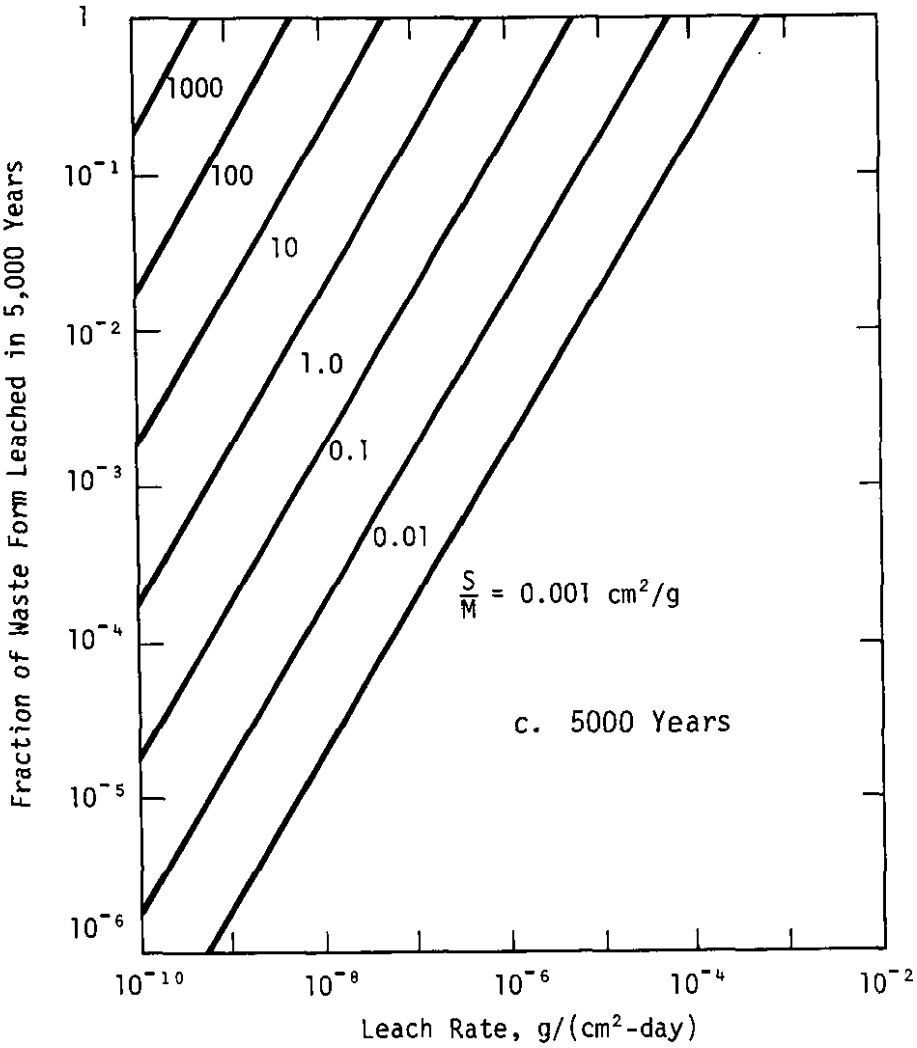

FIGURE 9c. Fraction of Waste Form Leached as a Function of Leach Rate (surface-to-mass ratios of 0.001 to 1000 cm^2/g) and Time (5000 years)

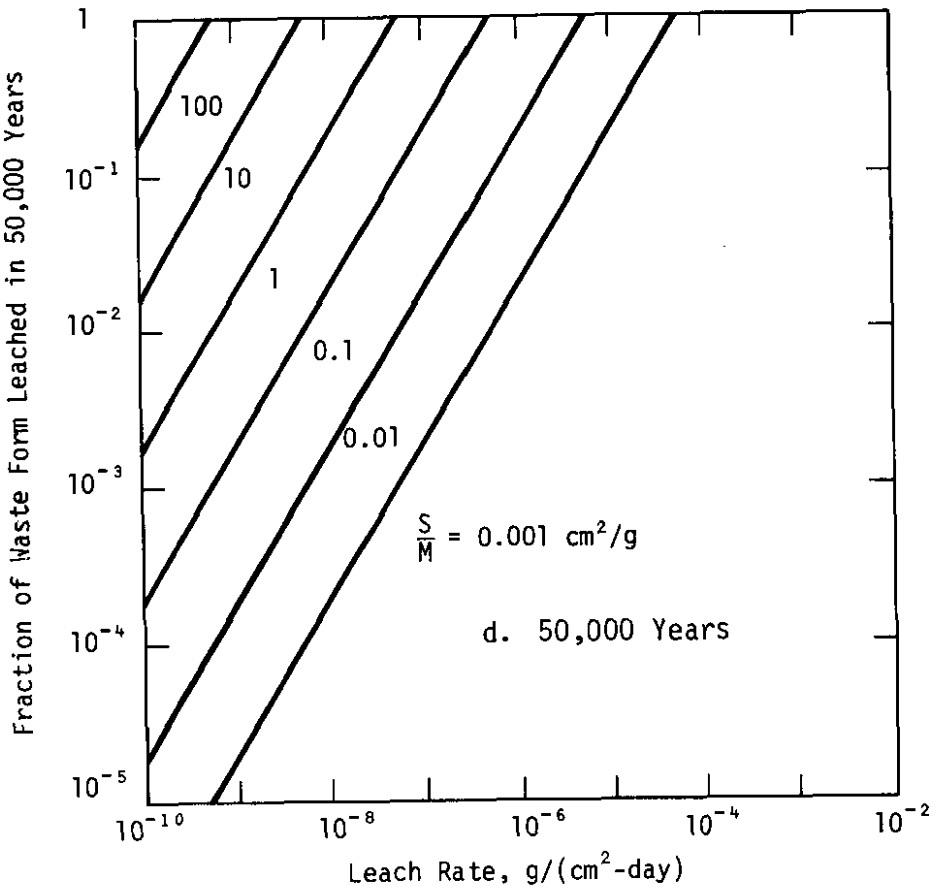

FIGURE 9d. Fraction of Waste Form Leached as a Function of Leach Rate (surface-to-mass ratios of 0.001 to 1000 cm^2/g) and Time (50,000 years)

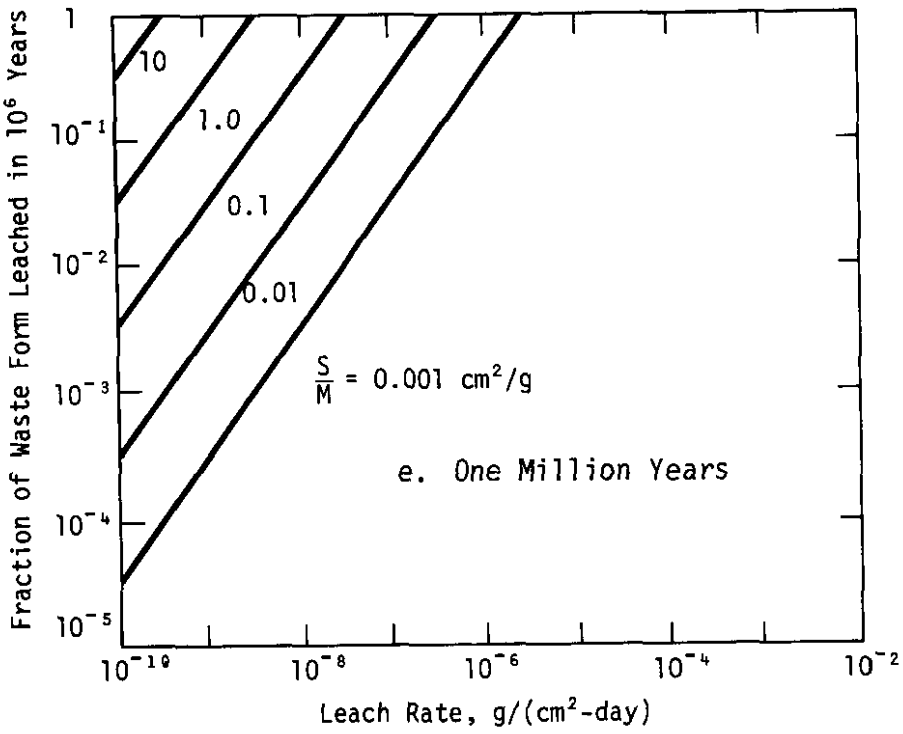

FIGURE 9e. Fraction of Waste Form Leached as a Function of Leach Rate (surface-to-mass ratios of 0.001 to 1000 cm^2/g) and Time (one million years)

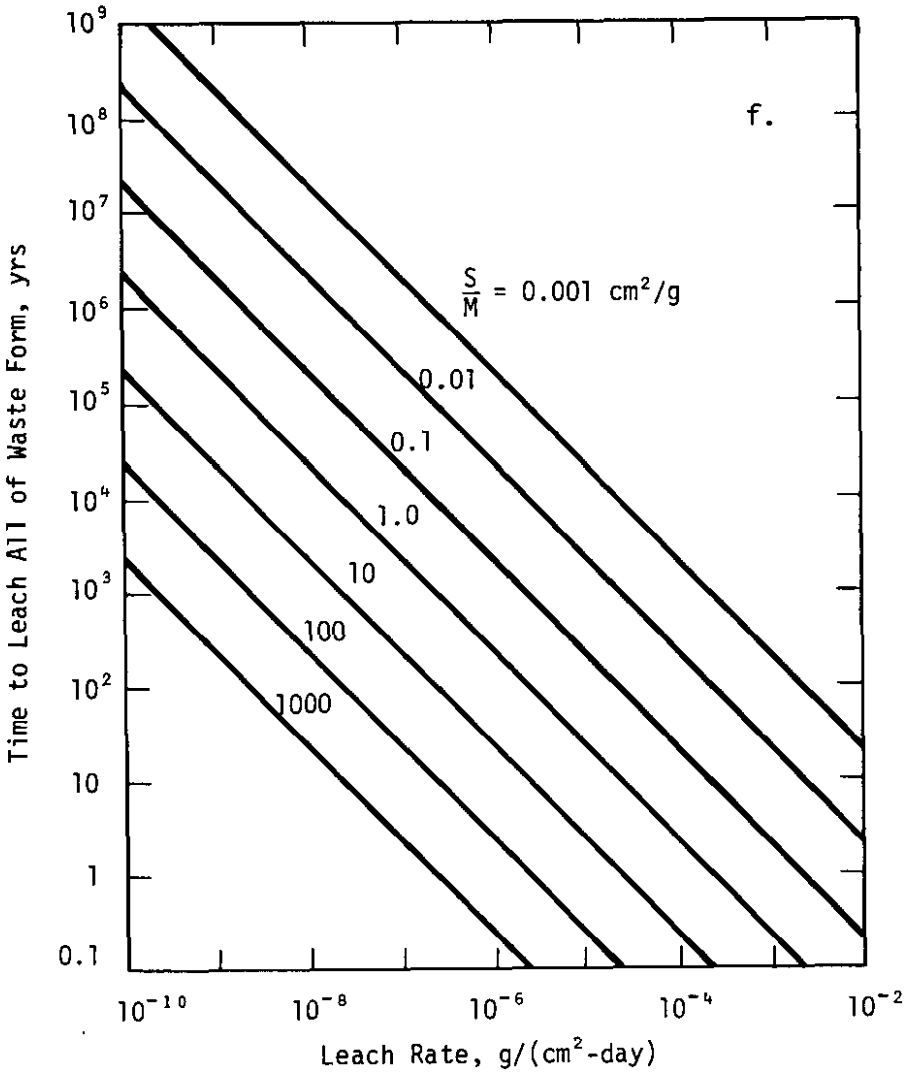

FIGURE 9f. Time to Leach All of Waste Form as a Function of Leach Rate for Surface-to-Mass Ratios of 0.001 to 1000 cm^2/g

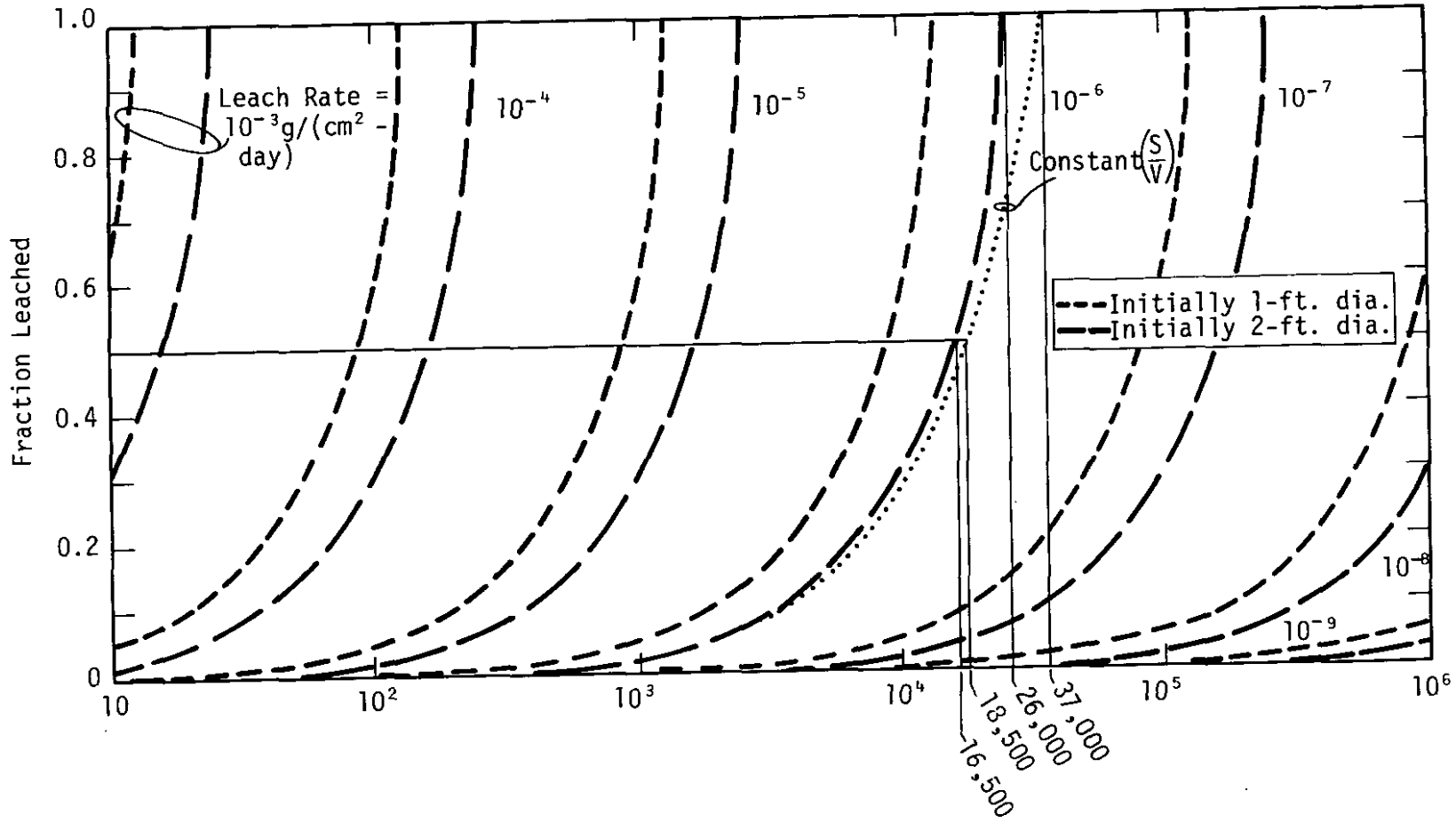

FIGURE 10. Fraction of Waste Form Leached from Cylinders at Leach Rates of 10^{-7} to 10^{-3} g/(cm^2-day)

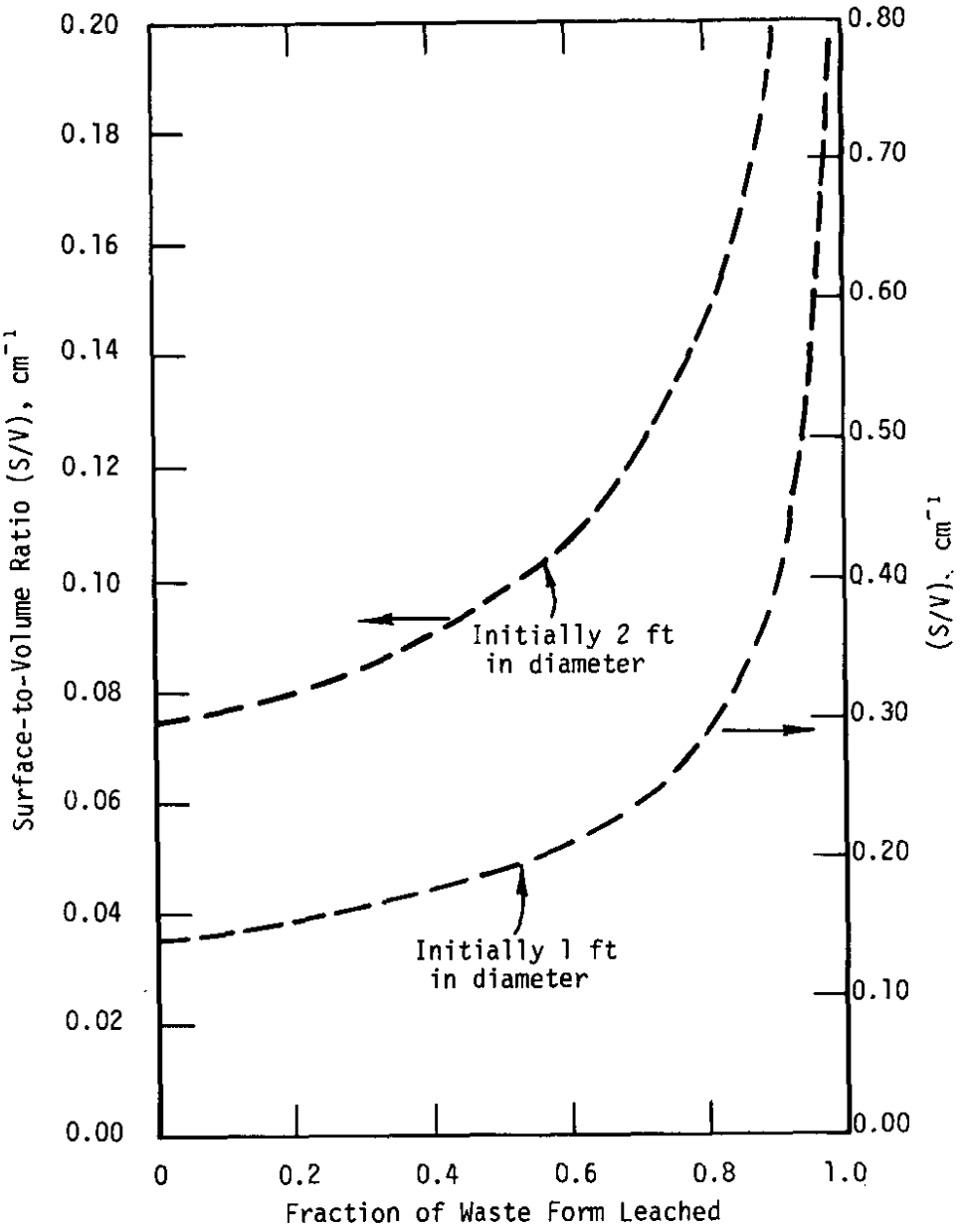

FIGURE 11. Change in Surface-to-Volume Ratio as a Cylindrical Waste Form is Leached

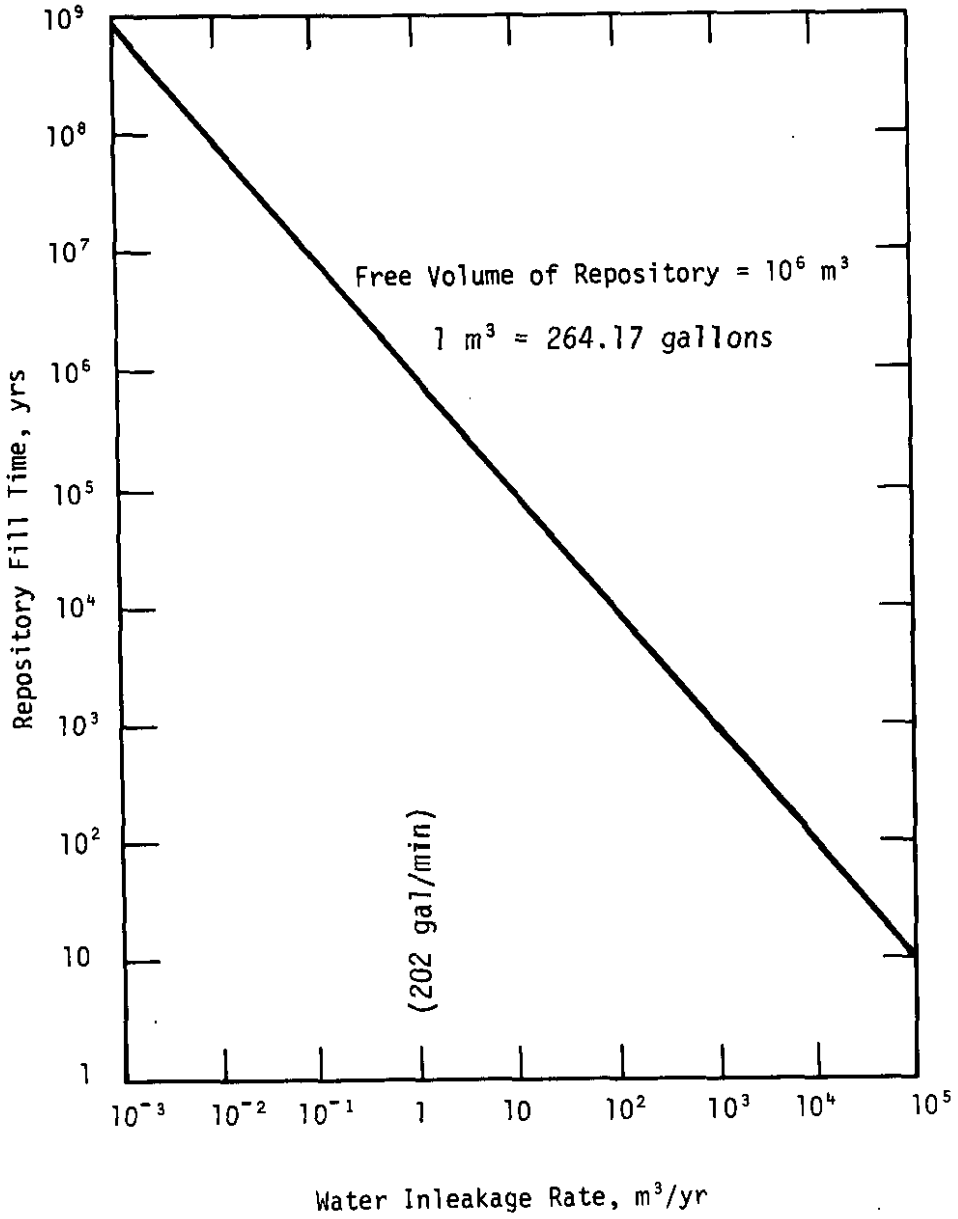

FIGURE 12. Fill Time of Repository as a Function of Water Inleakage Rate

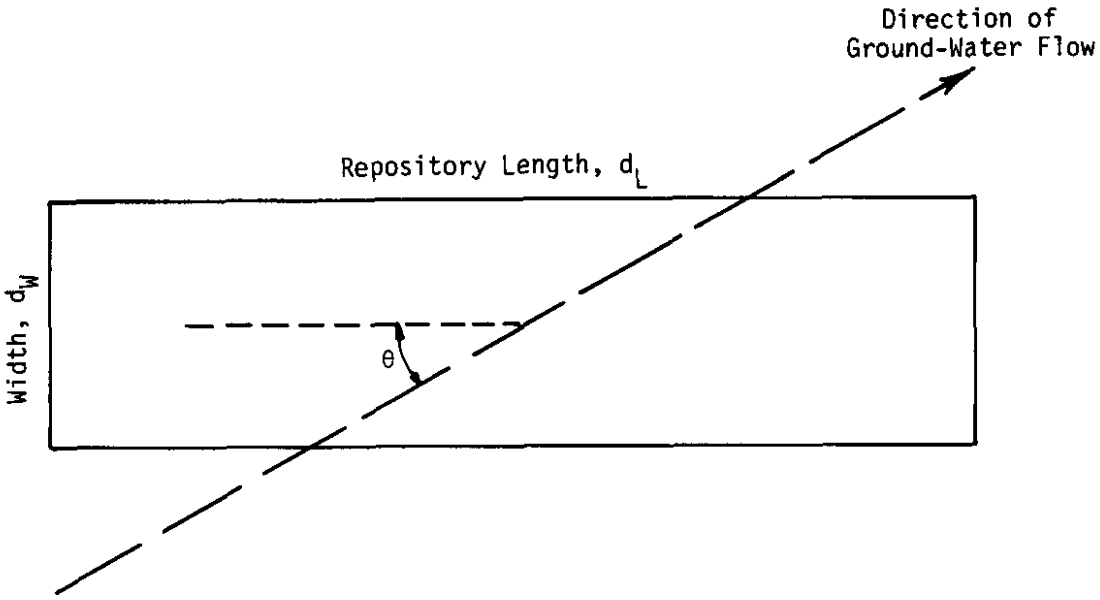

FIGURE 13. Orientation of Repository with Respect to Direction of Groundwater Flow

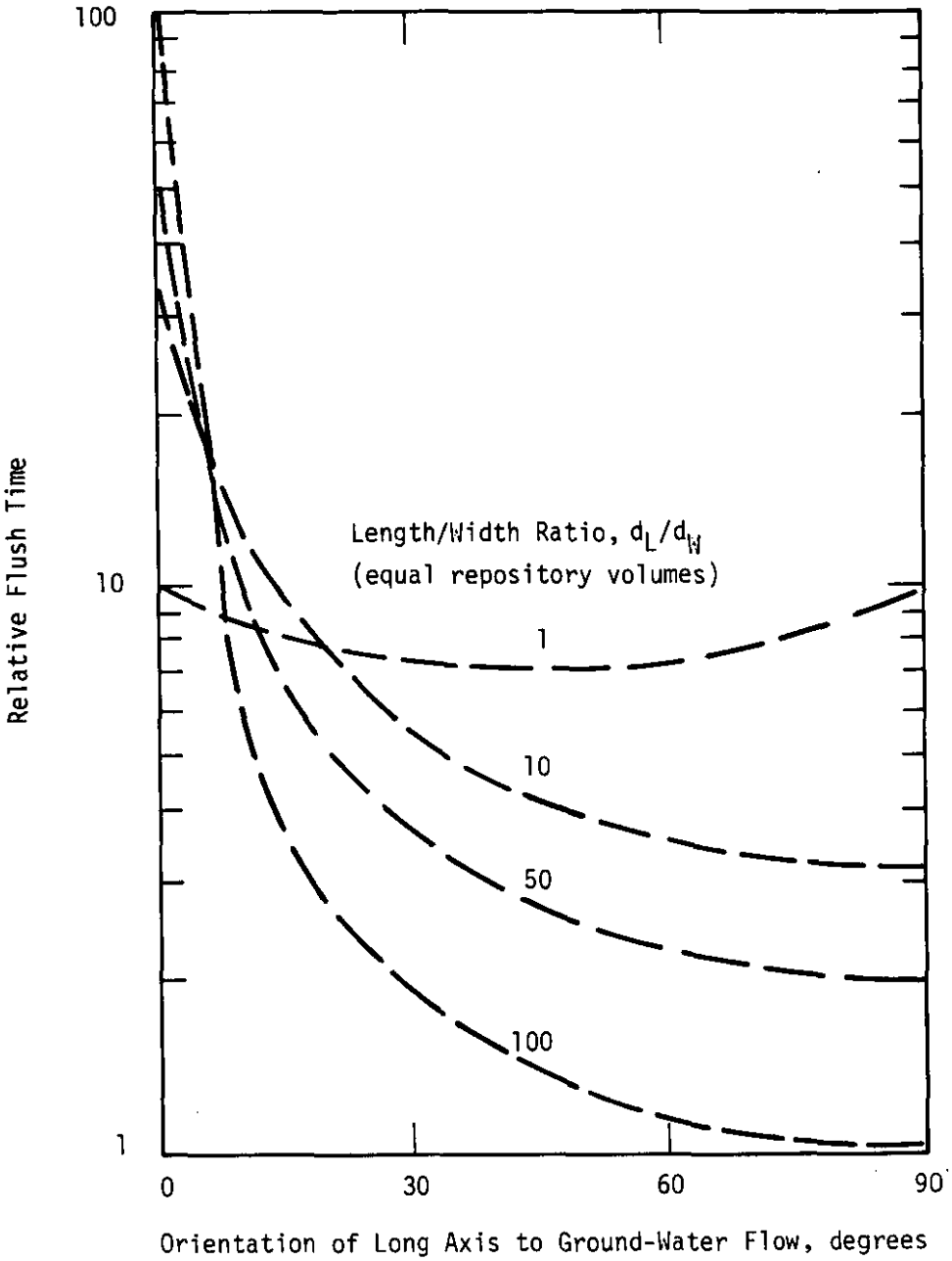

FIGURE 14. Relative Flush Time of Repository as a Function of Direction of Groundwater Flow (for d_L/d_W ratios of 1/1 to 100/1)

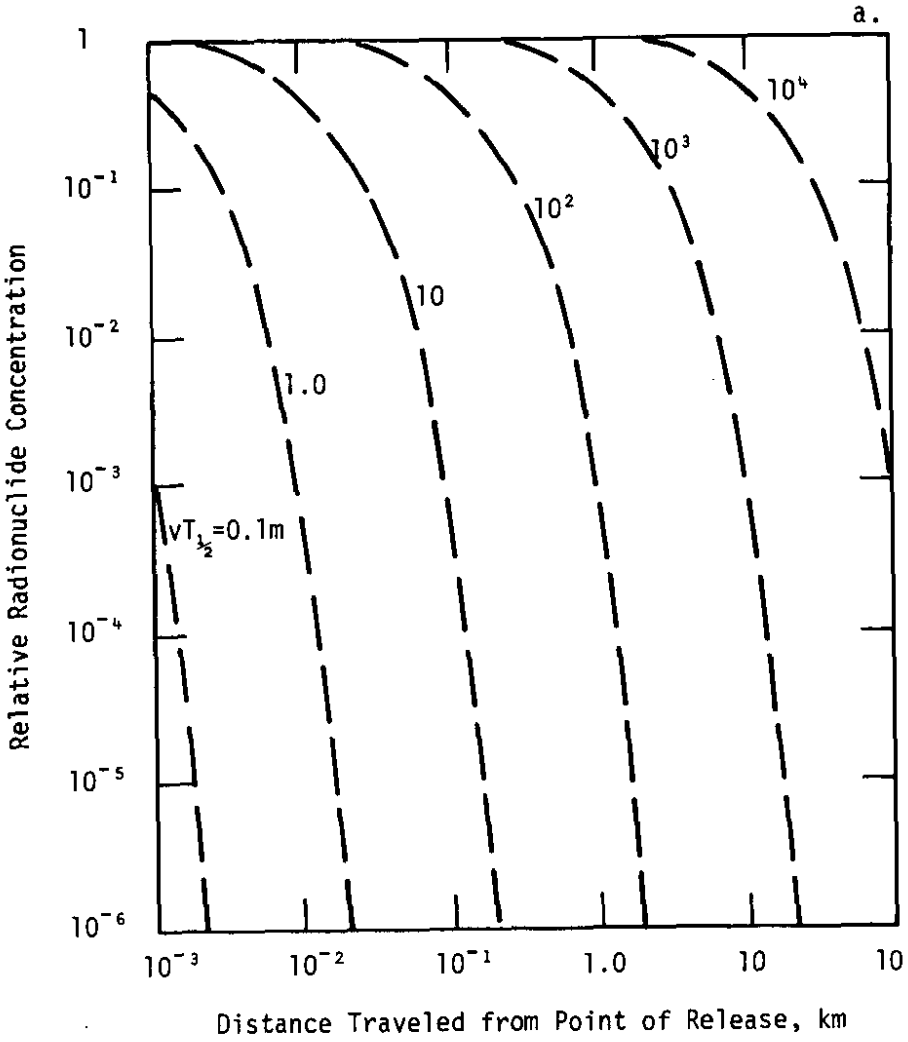

FIGURE 15a. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for reduced time factors, $vT_{\frac{1}{2}}$, of 0.1 m to 10 km)

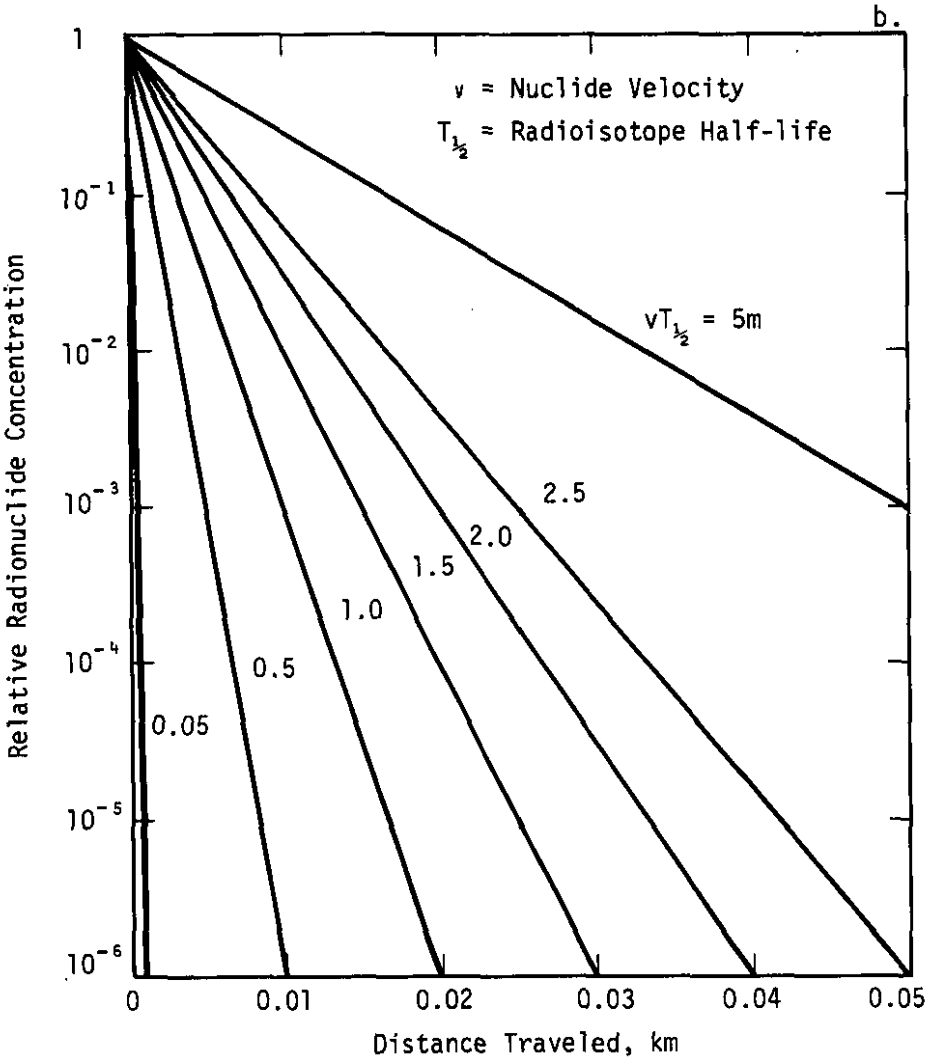

FIGURE 15b. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for reduced time of 0.05 m to 5 m)

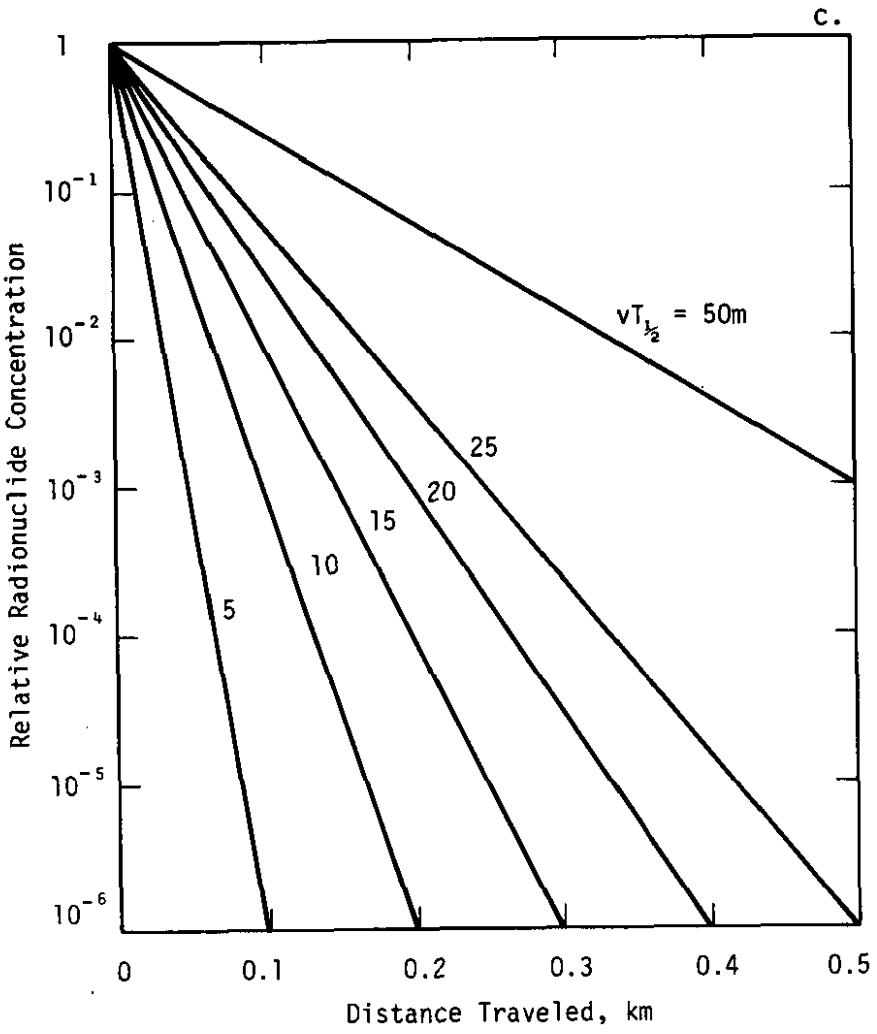

FIGURE 15c. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for reduced time of 5 m to 50 m)

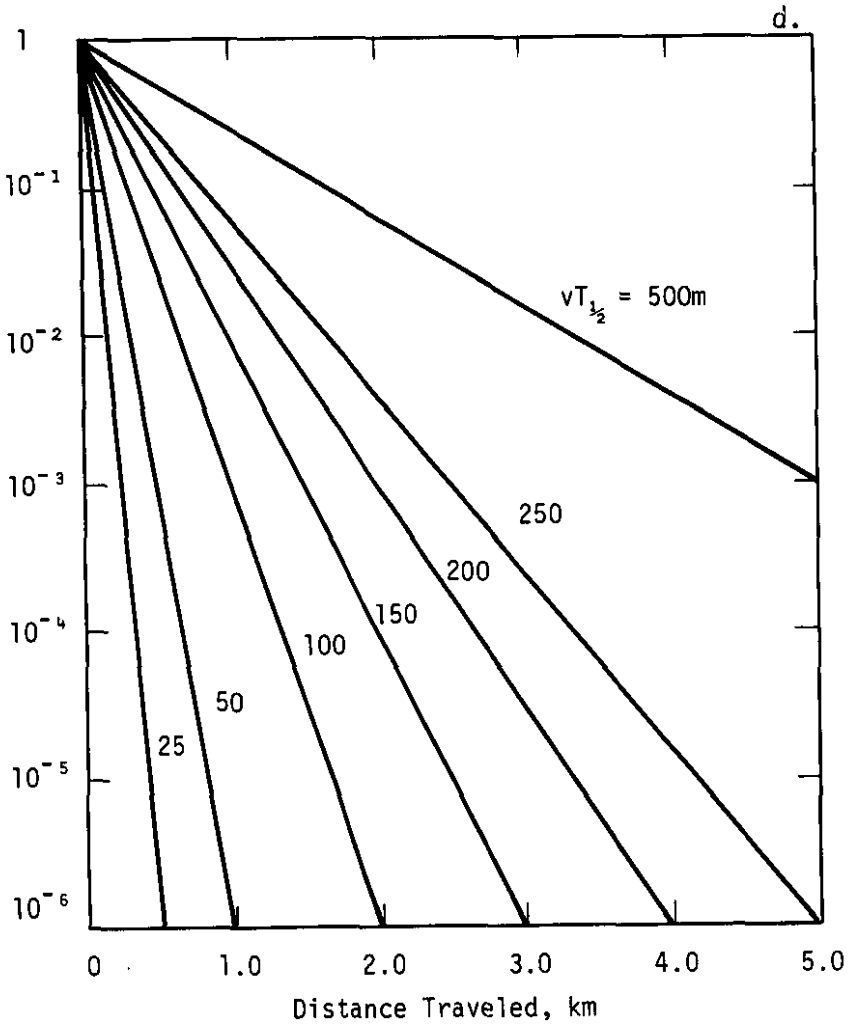

FIGURE 15d. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for reduced time of 25 m to 500 m)

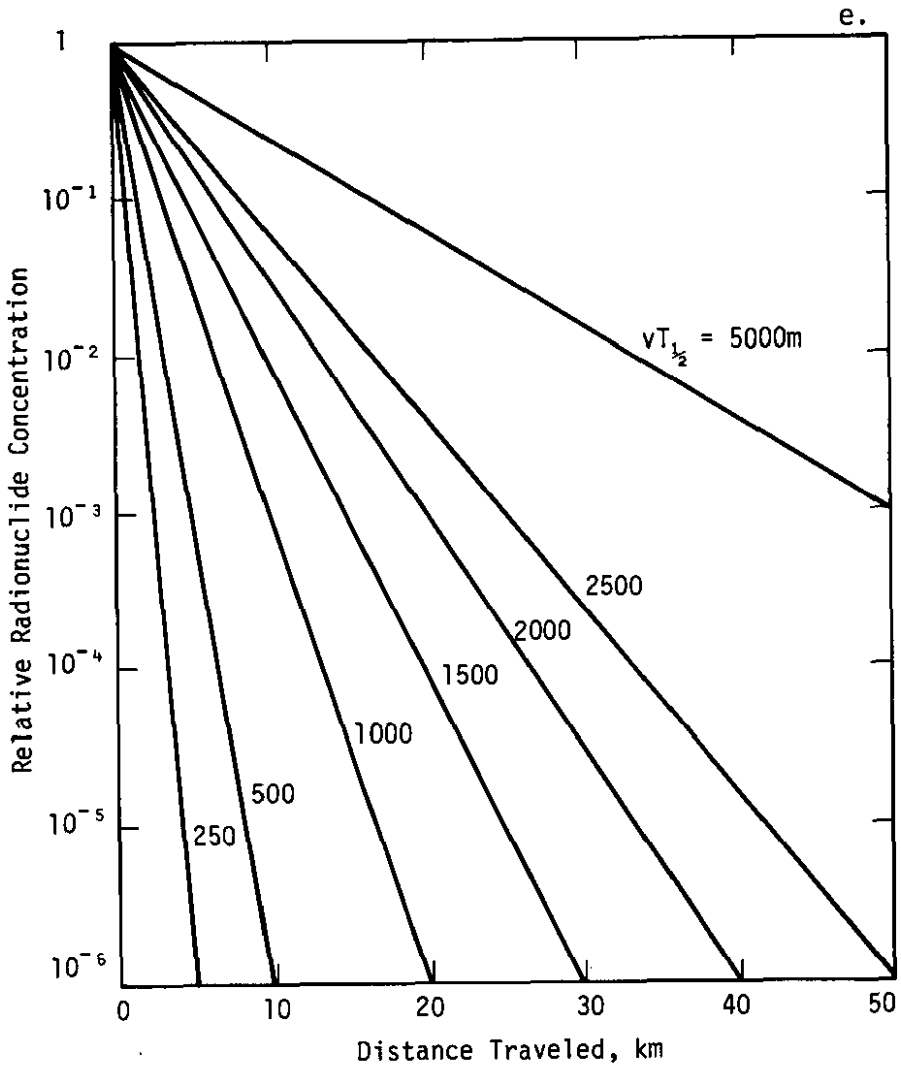

FIGURE 15e. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for reduced time of 250 m to 5000 m)

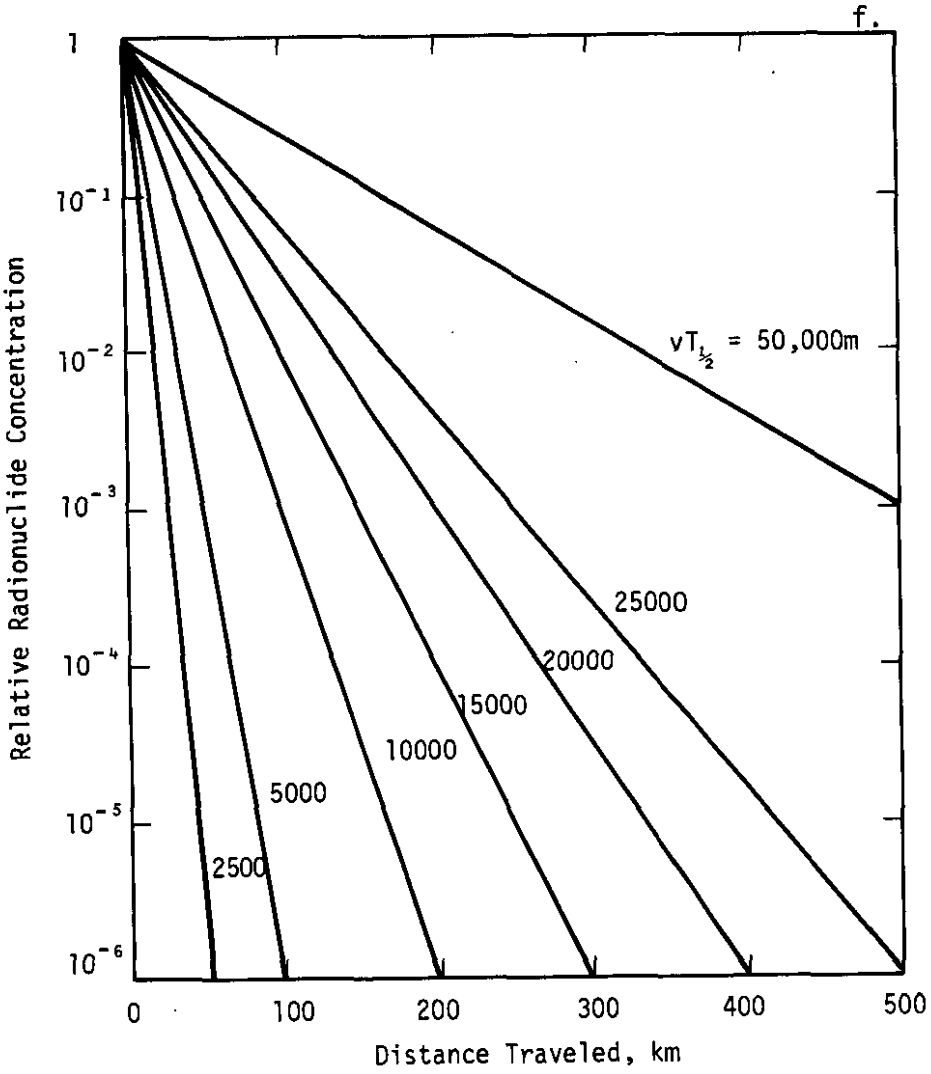

FIGURE 15f. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for reduced time of 2500 m to 50 km)

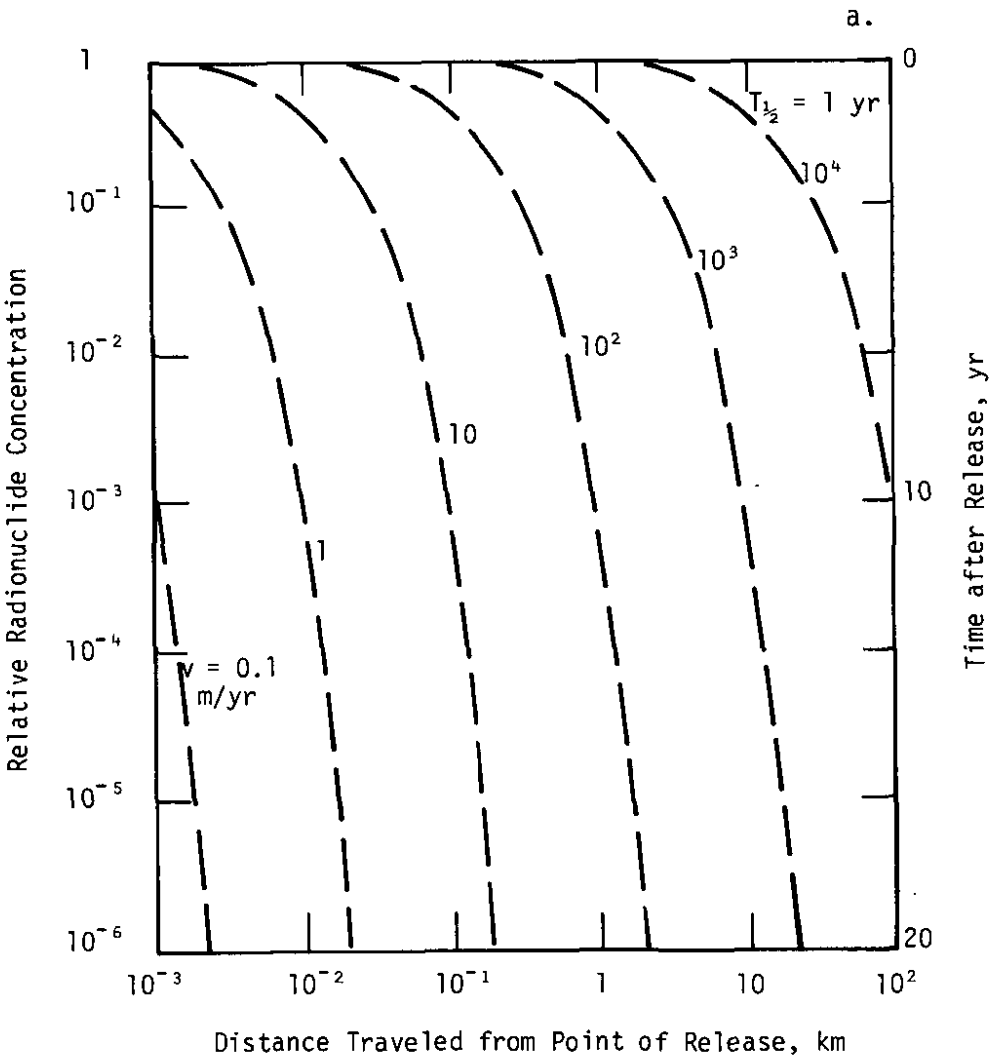

FIGURE 16a. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for half-lives, $T_{1/2}$, of 1 yr and velocities, v, of 0.1 m/yr to 10 km/yr)

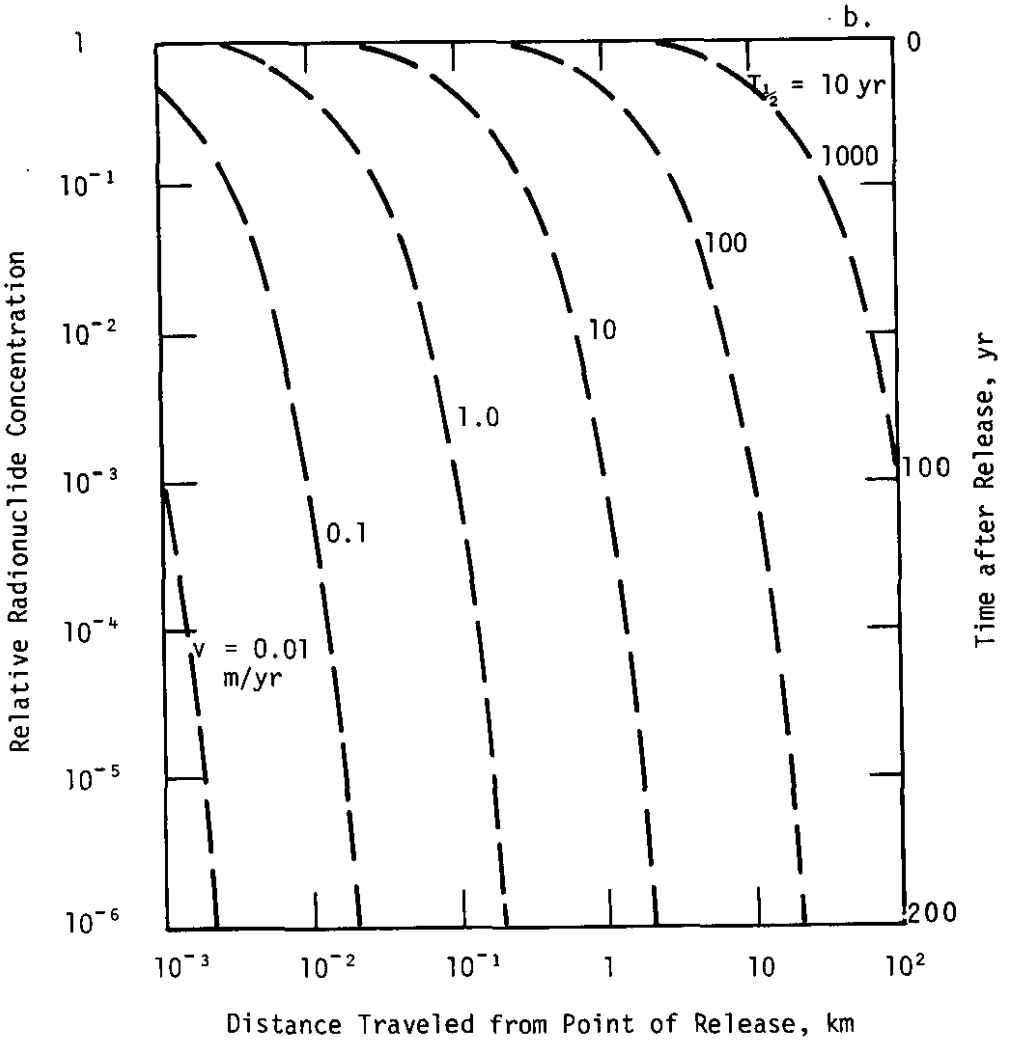

FIGURE 16b. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for half-lives, $T_{1/2}$, of 10 yr and velocities, v, of 0.01 m/yr to 1000 m/yr)

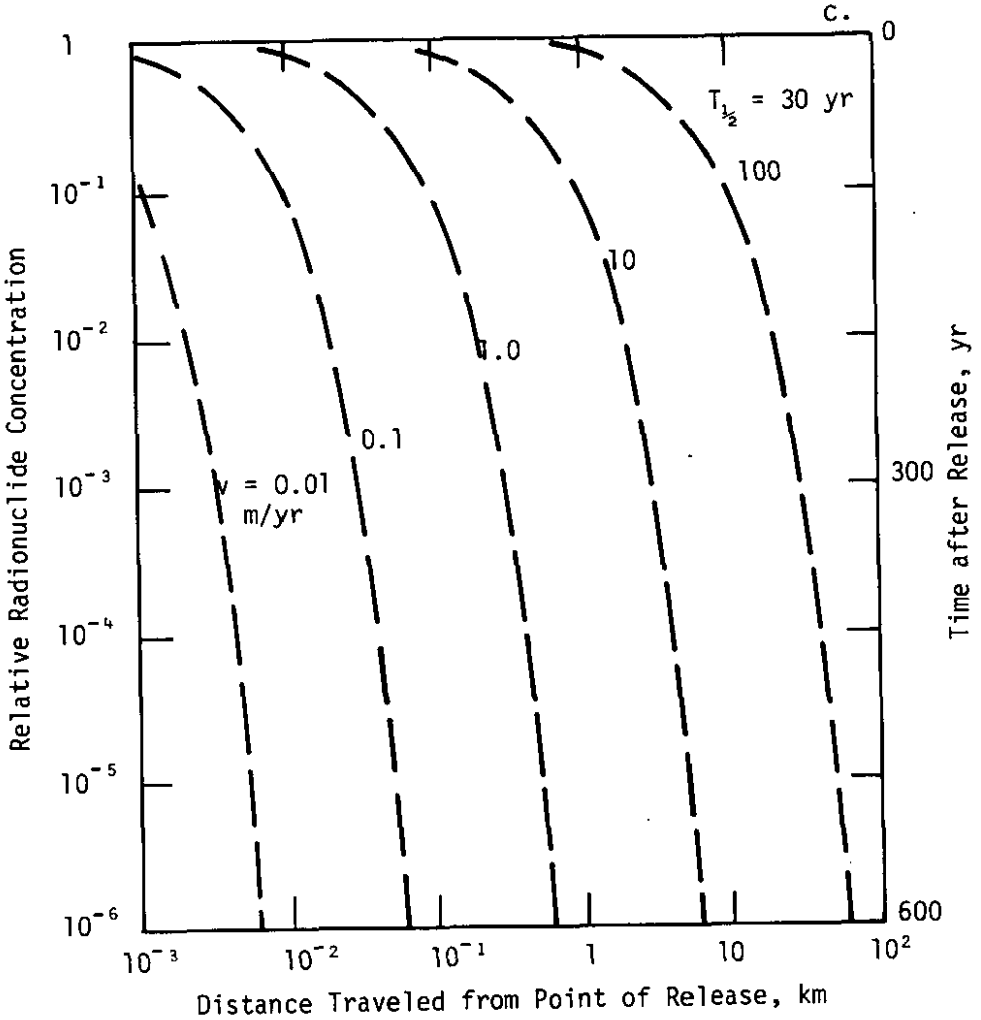

FIGURE 16c. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for half-lives, $T_{\frac{1}{2}}$, of 30 yr and velocities, v, of 0.01 m/yr to 100 m/yr)

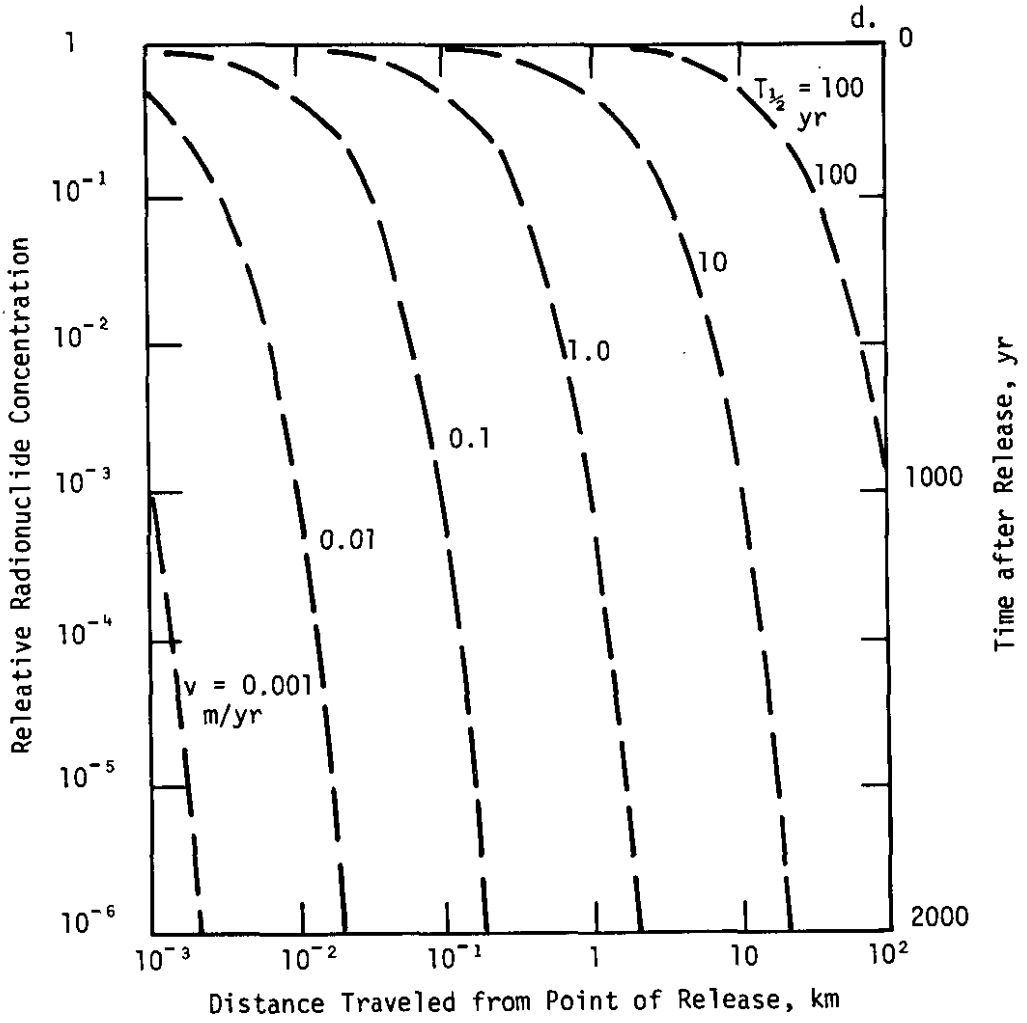

FIGURE 16d. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for half-lives, $T_{1/2}$, of 100 yr and velocities, v, of 0.001 m/yr to 100 m/yr)

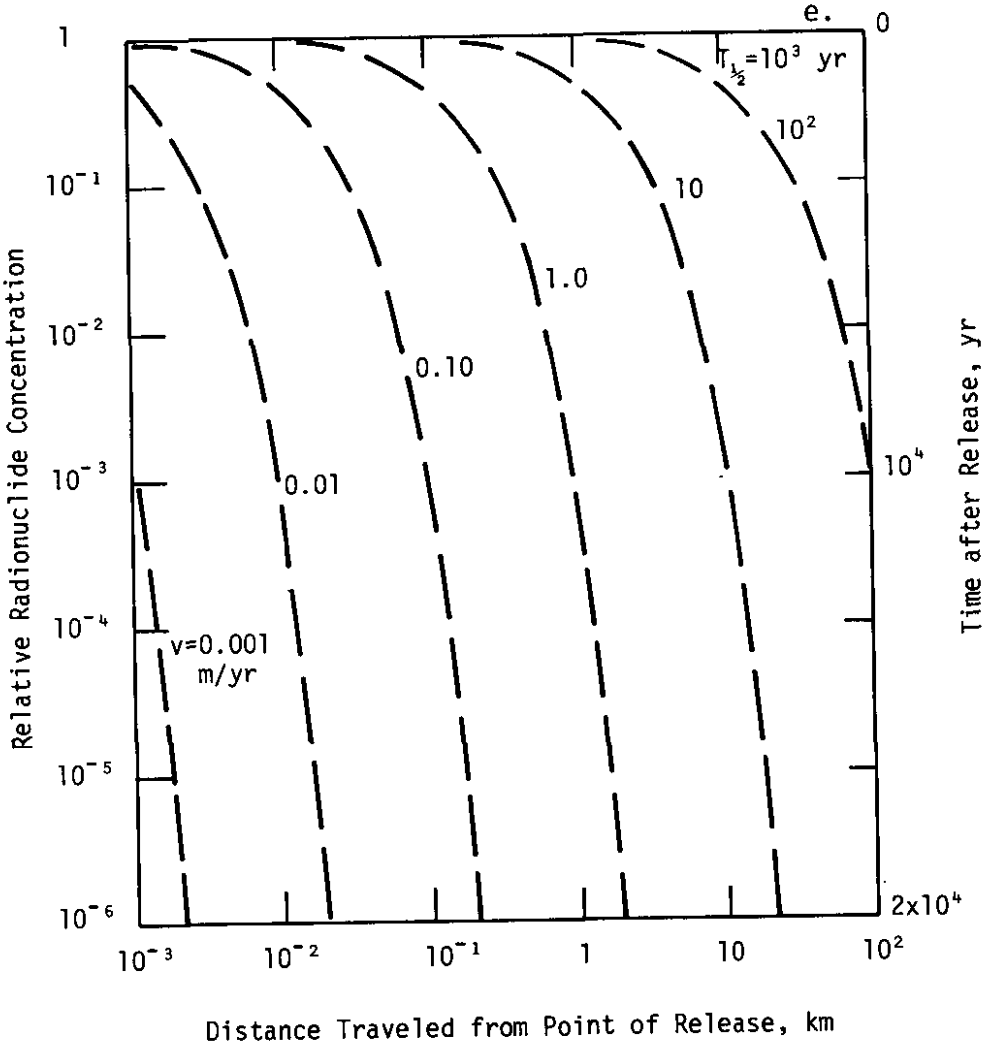

FIGURE 16e. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for half-lives, $T_{1/2}$, of 1000 yr and velocities, v, of 0.001 m/yr to 100 m/yr)

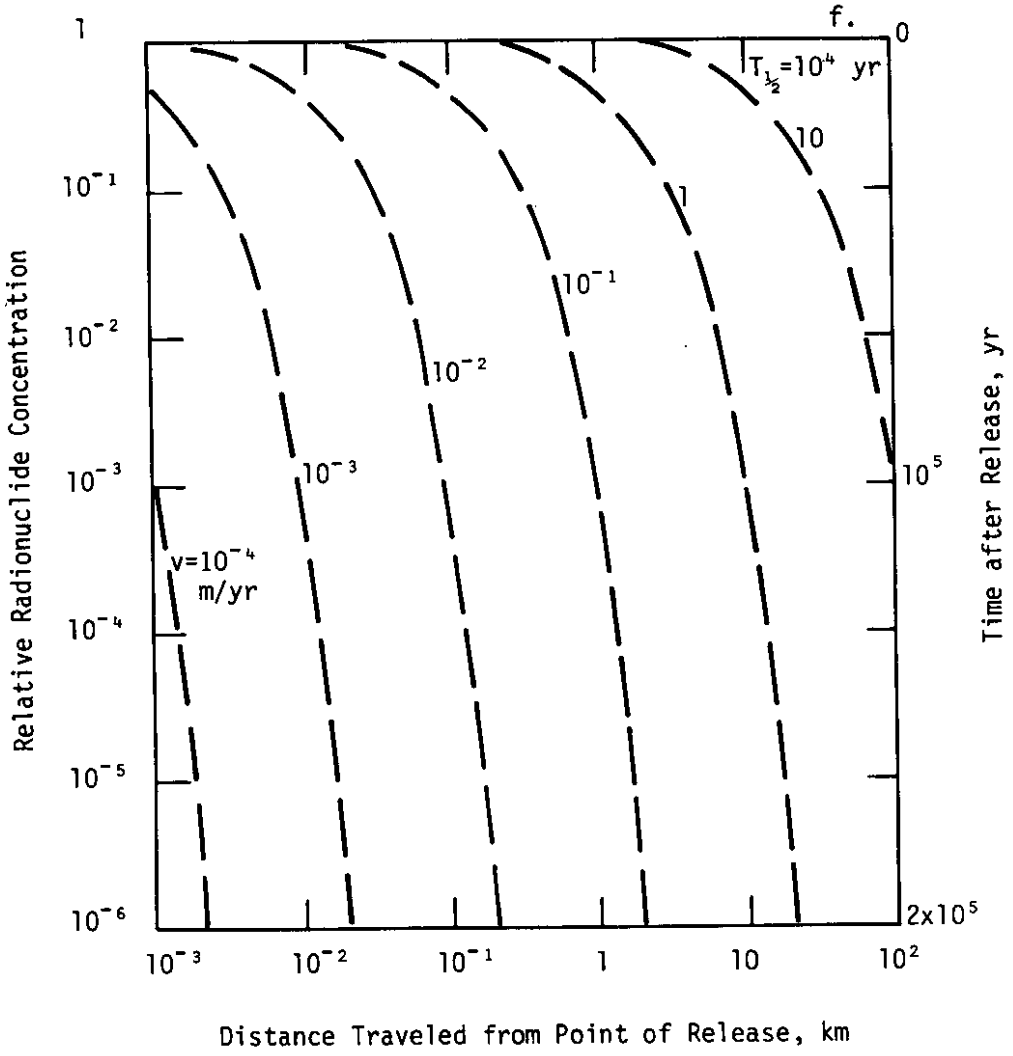

FIGURE 16f. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for half-lives, $T_{\frac{1}{2}}$, of 10,000 yr and velocities, v, of 0.0001 m/yr to 10 m/yr)

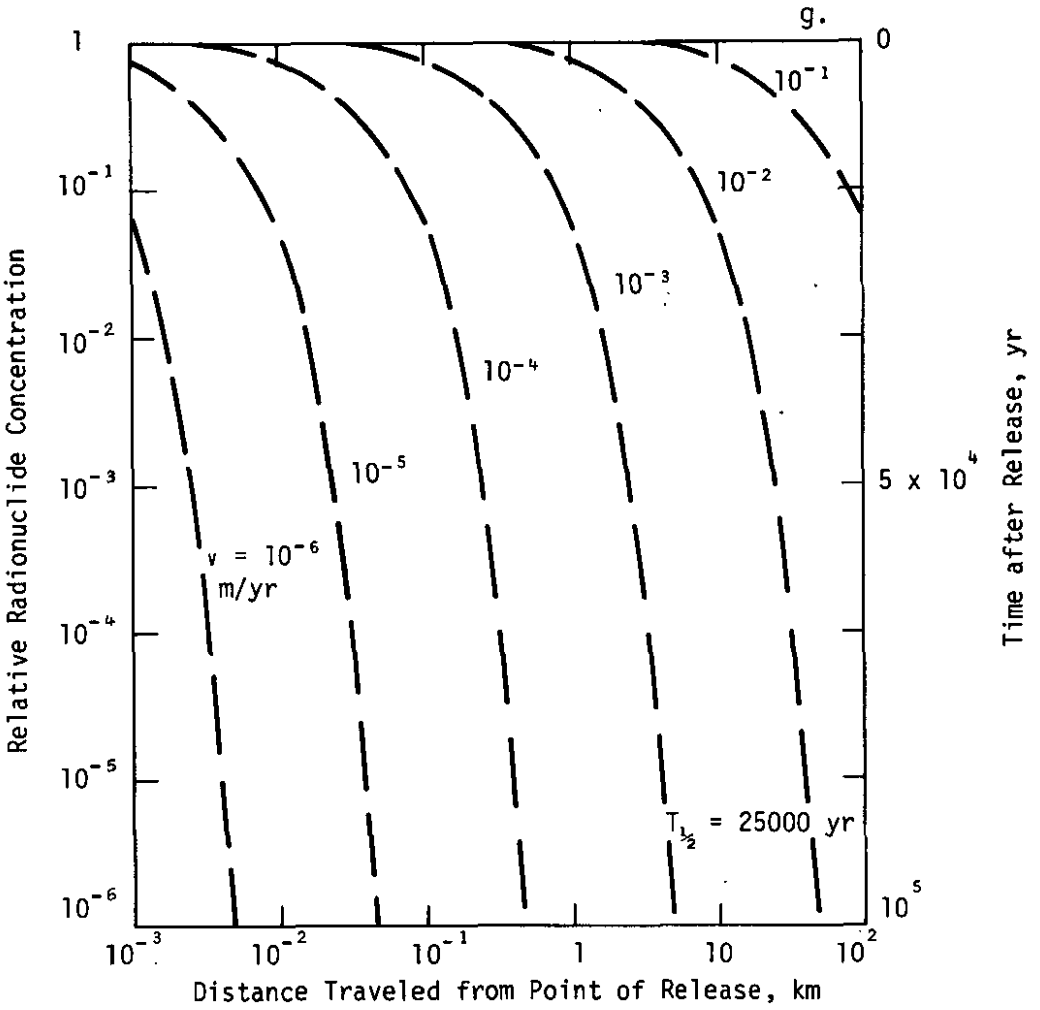

FIGURE 16g. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for half-lives, $T_{\frac{1}{2}}$, 25,000 yr and velocities, v, of 10^{-6} m/yr to 0.10 m/yr)

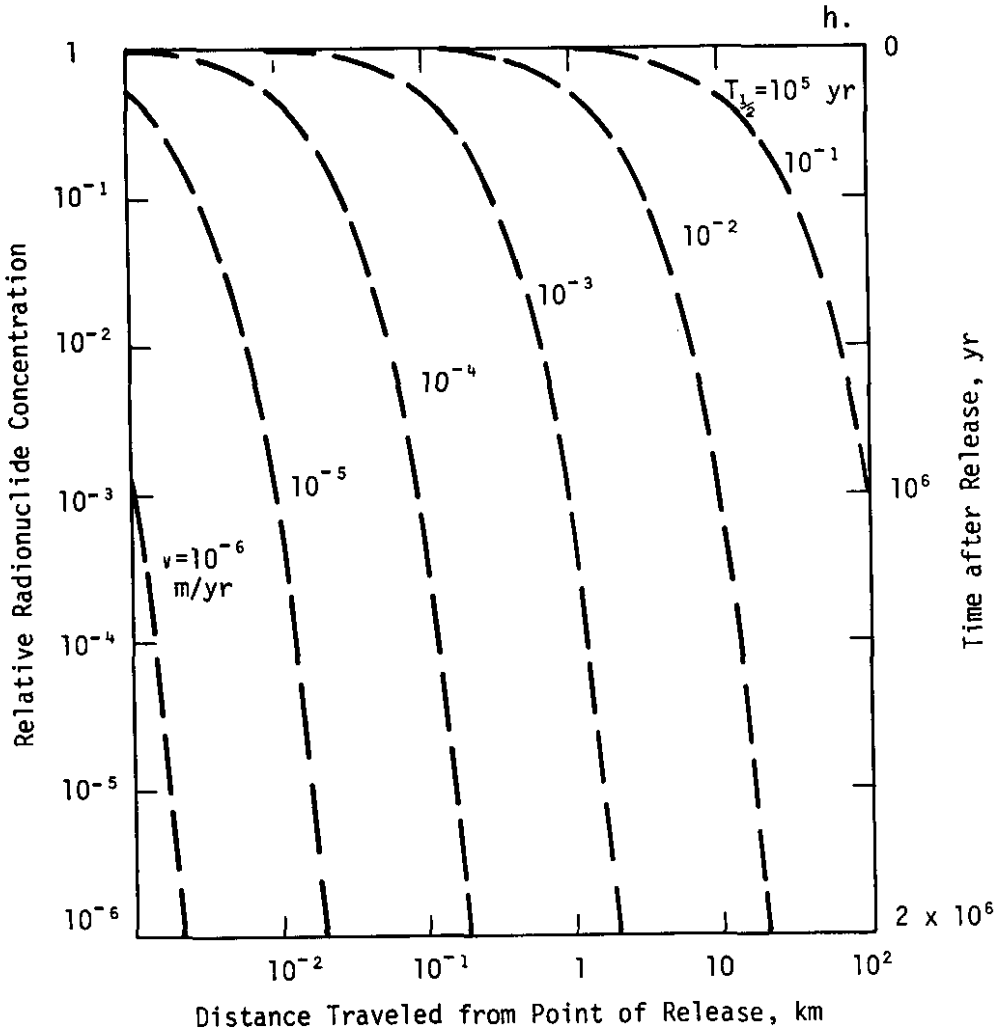

FIGURE 16h. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for half-lives, $T_{1/2}$, of 100,000 yr and velocities, v, of 10^{-6} m/yr to 0.10 m/yr)

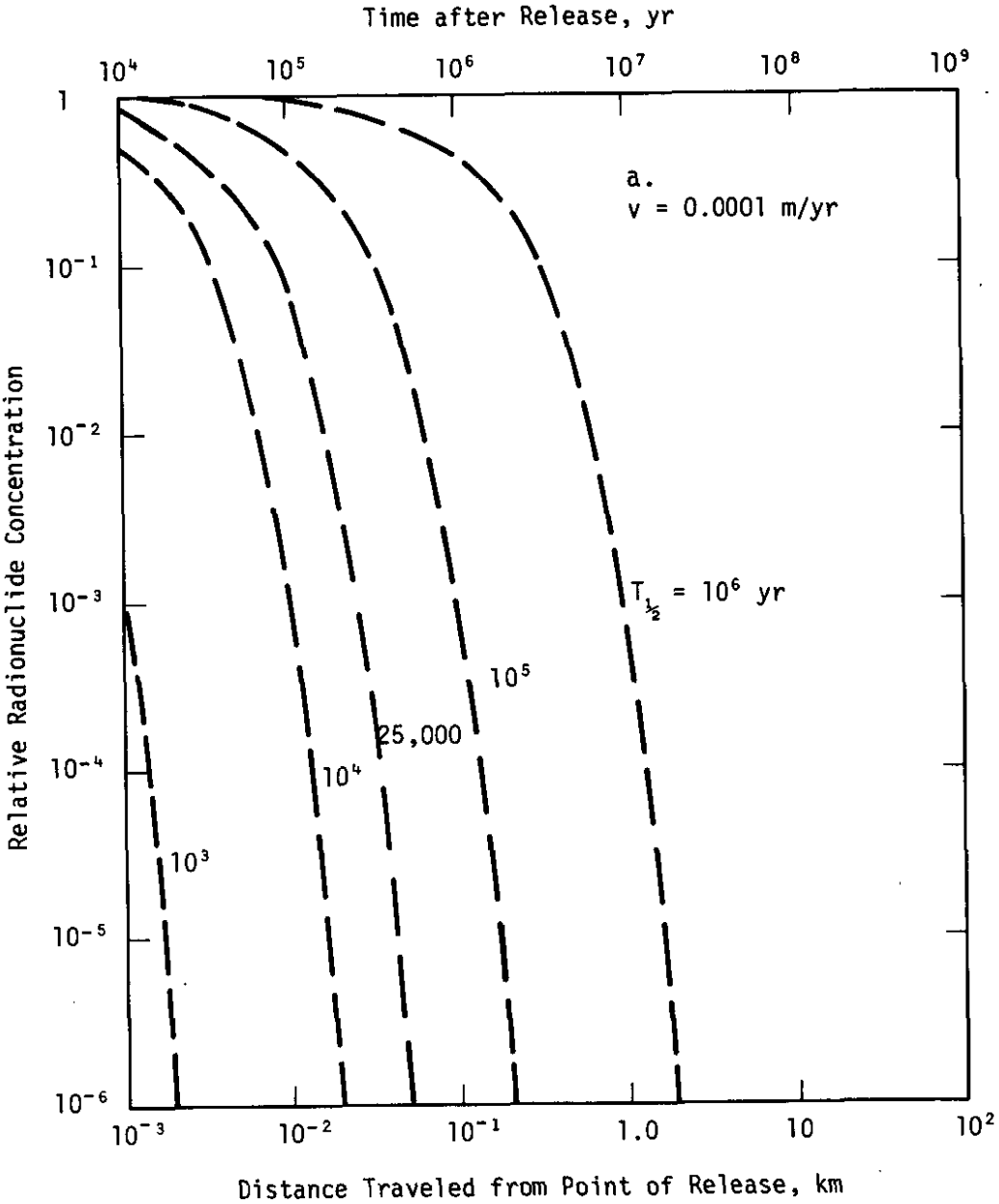

FIGURE 17a. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for a velocity, v, of 10^{-4} m/yr and half-lives, $T_{\frac{1}{2}}$, of 1000 yr to one million yr)

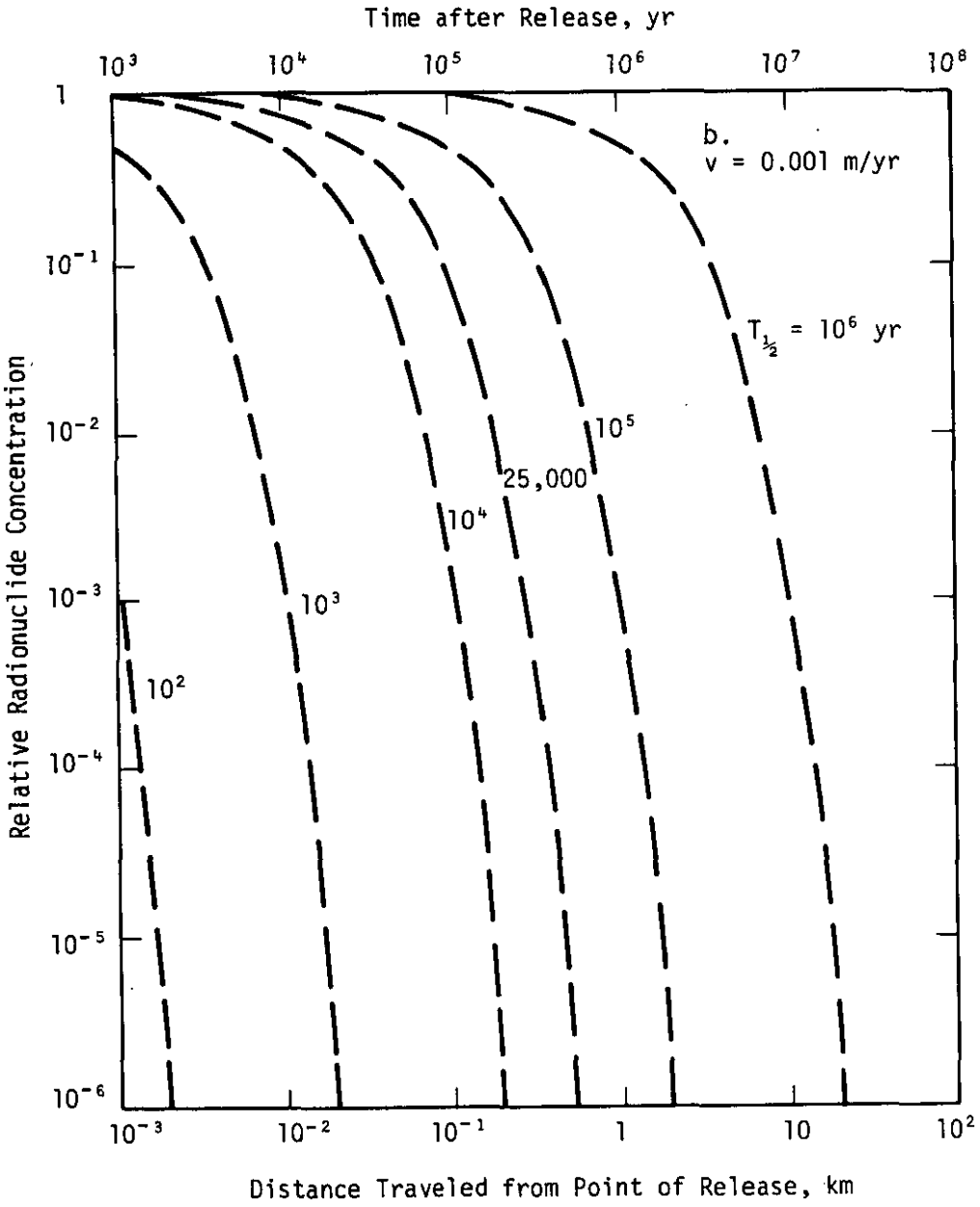

FIGURE 17b. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for a velocity, v, of 1 mm/yr and half-lives, $T_{\frac{1}{2}}$, of 100 yr to one million yr)

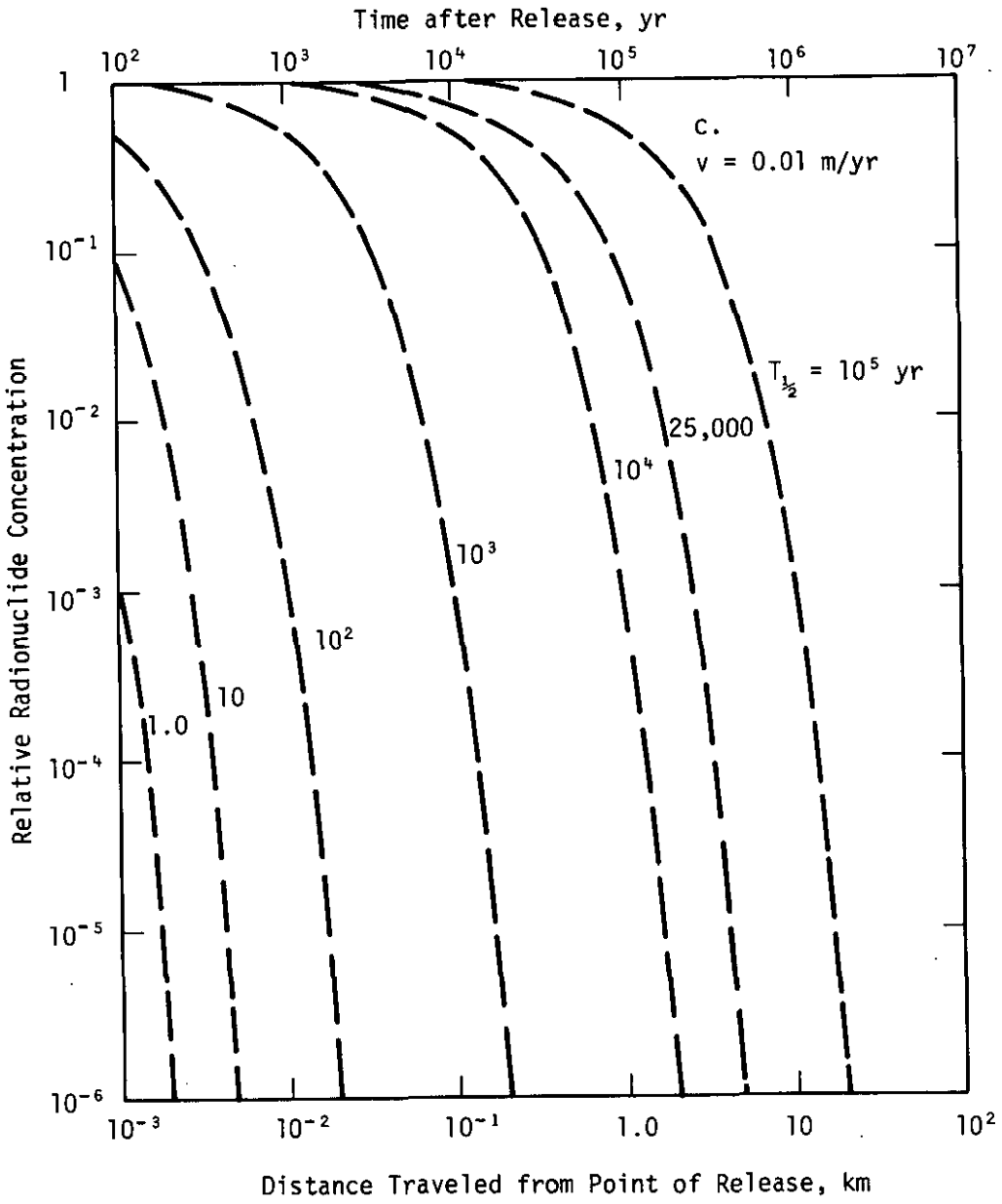

FIGURE 17c. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for a velocity, v, of 10 mm/yr and half-lives, $T_{1/2}$, of 1 yr to 100,000 yr)

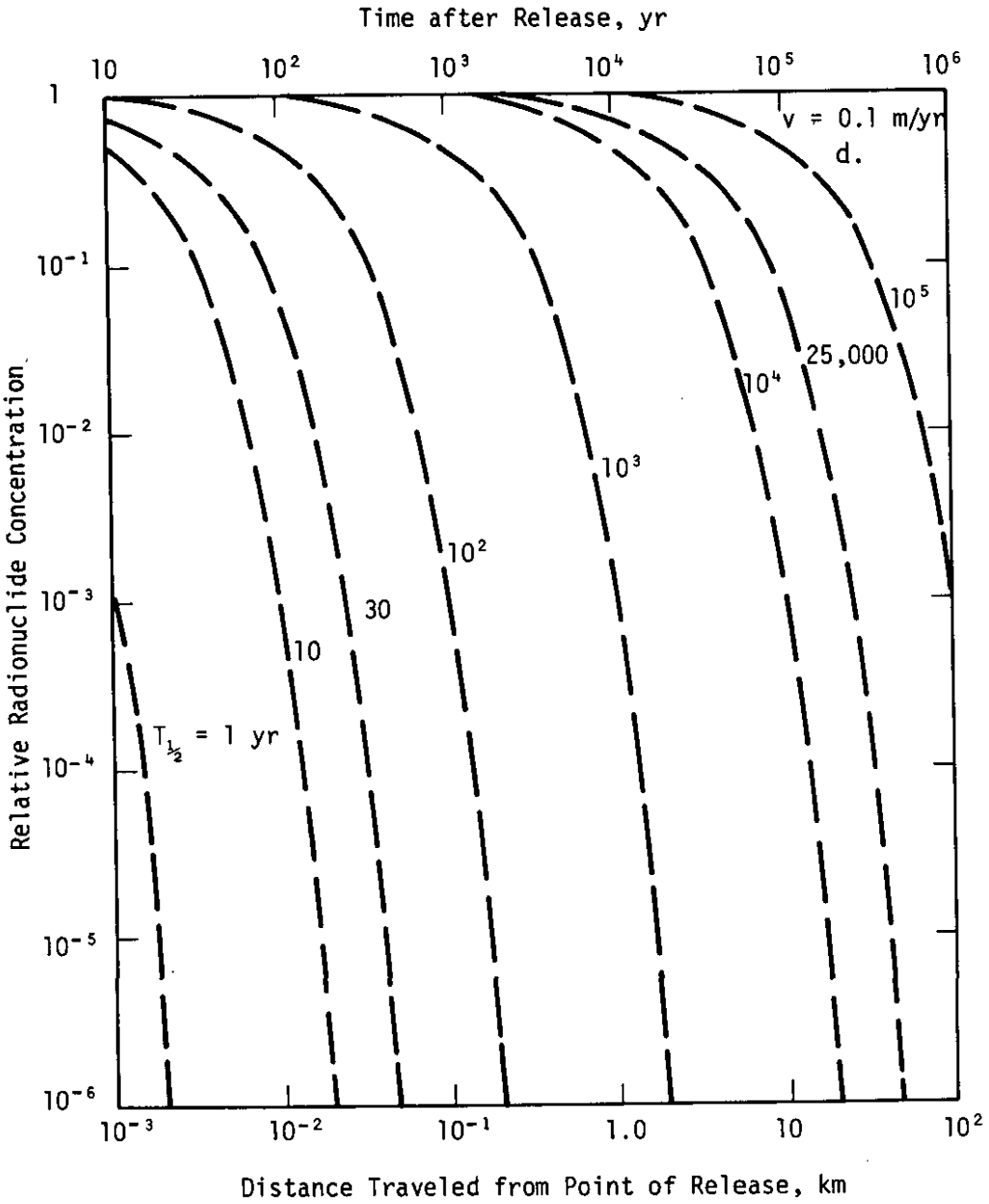

FIGURE 17d. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for a velocity, v, of 0.1 m/yr and half-lives, $T_{1/2}$, of 1 yr to 100,000 yr)

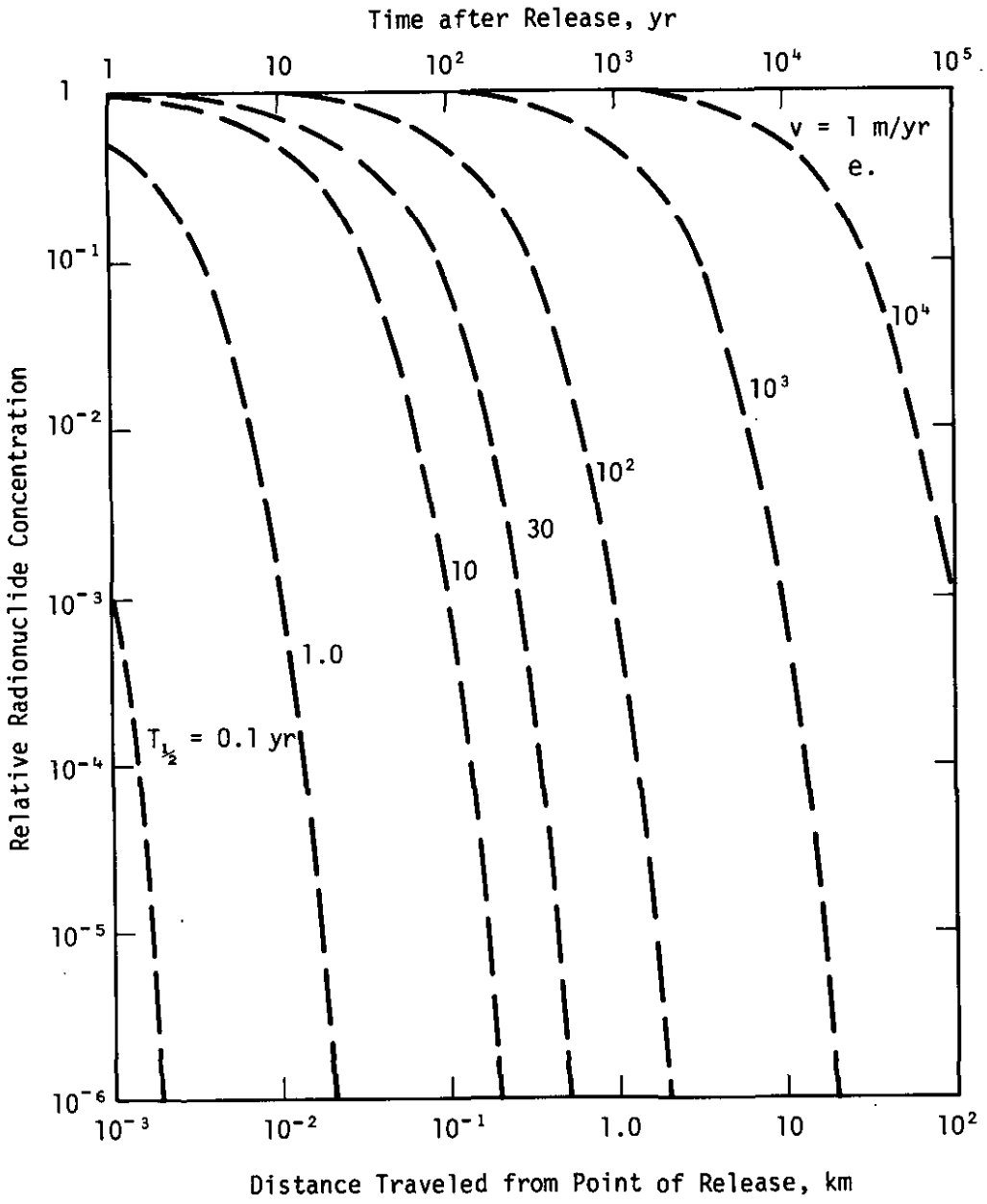

FIGURE 17e. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for a velocity, v, of 1 m/yr and half-lives, $T_{1/2}$, of 0.1 yr to 10,000 yr)

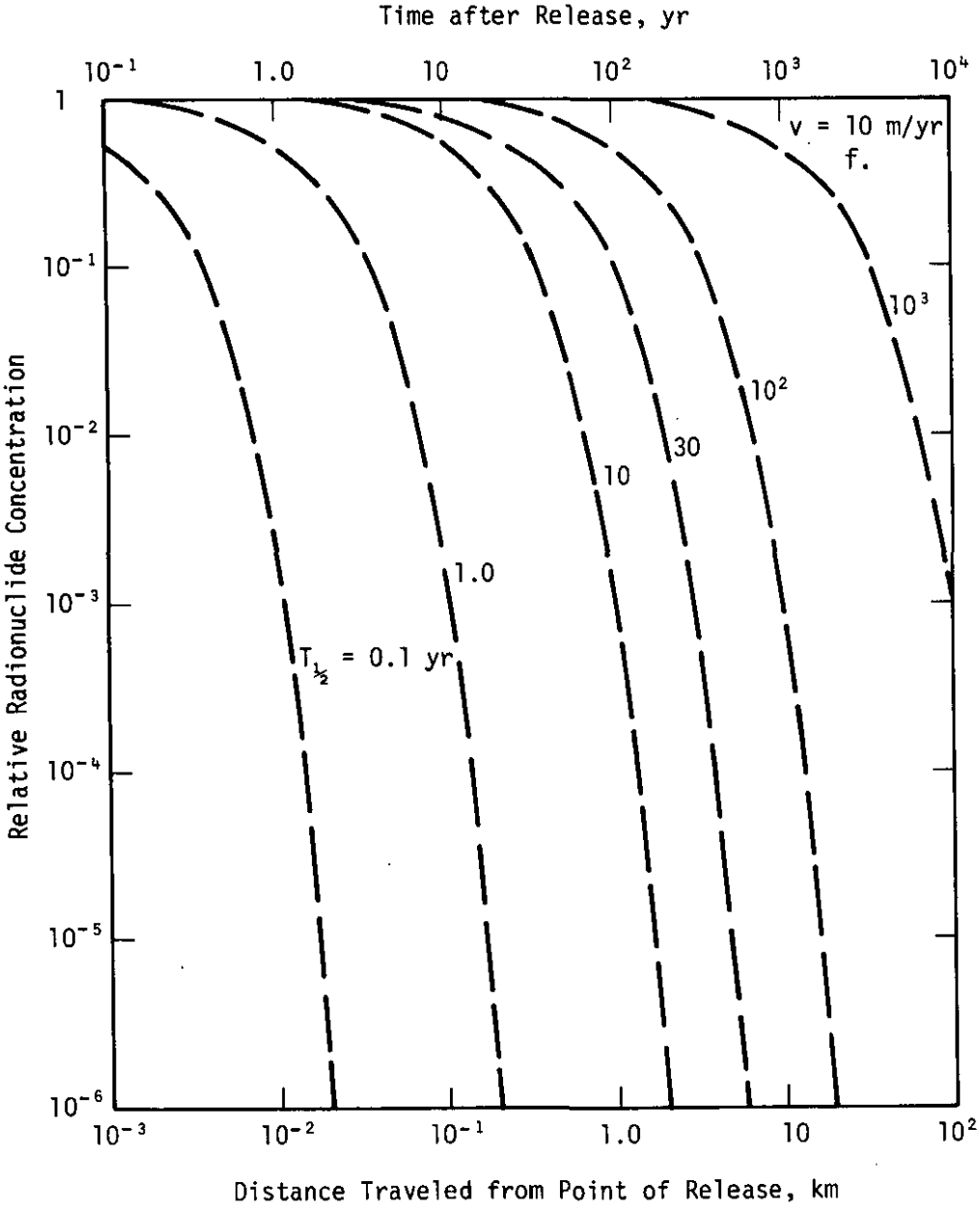

FIGURE 17f. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for a velocity, v, of 10 m/yr and half-lives, $T_{\frac{1}{2}}$, of 0.1 yr to 1000 yr)

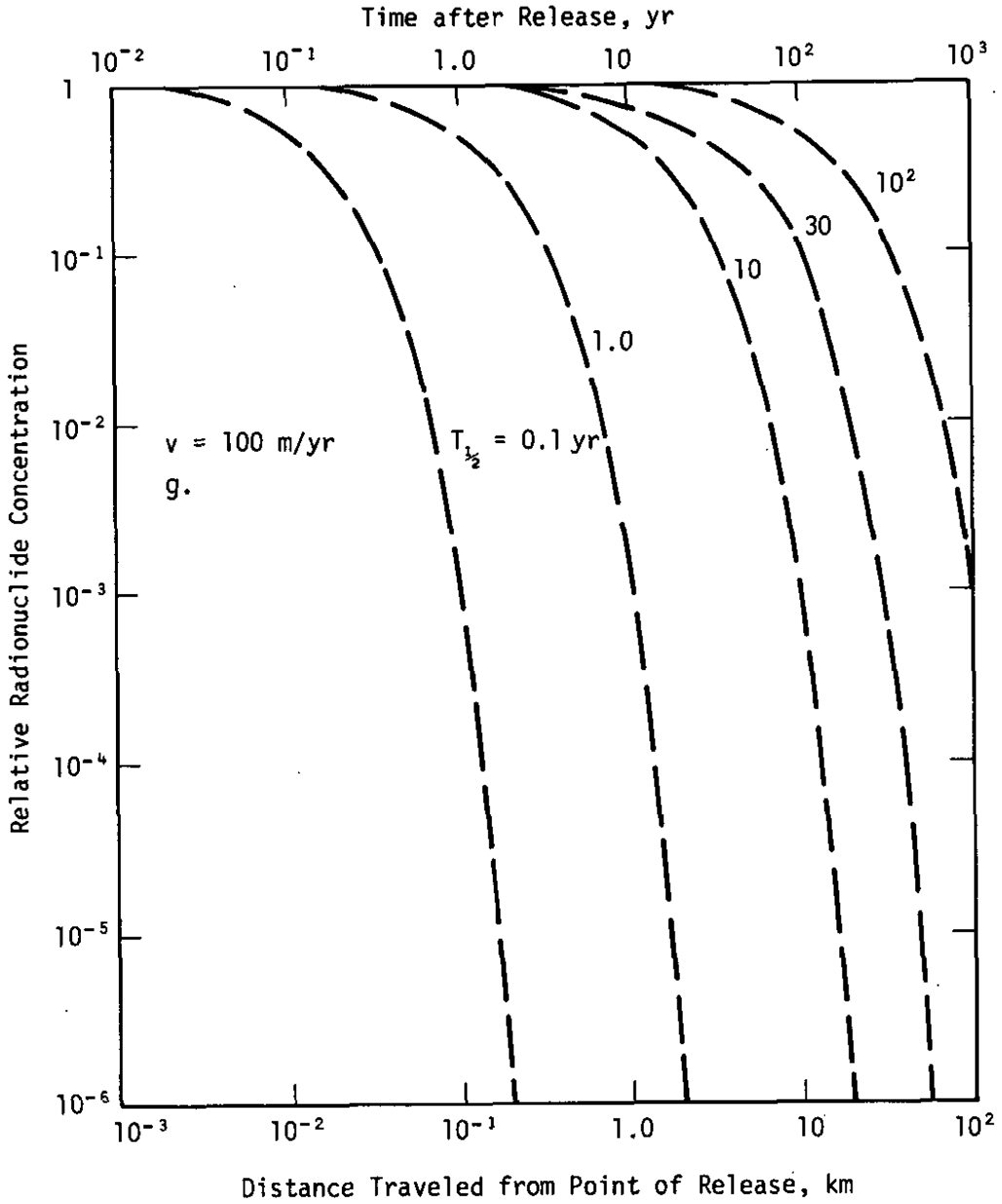

FIGURE 17g. Relative Concentrations of Radionuclides with Travel Distance from Point of Release (for a velocity, v, of 100 m/yr and half-lives, $T_{\frac{1}{2}}$, of 0.1 yr to 100 yr)

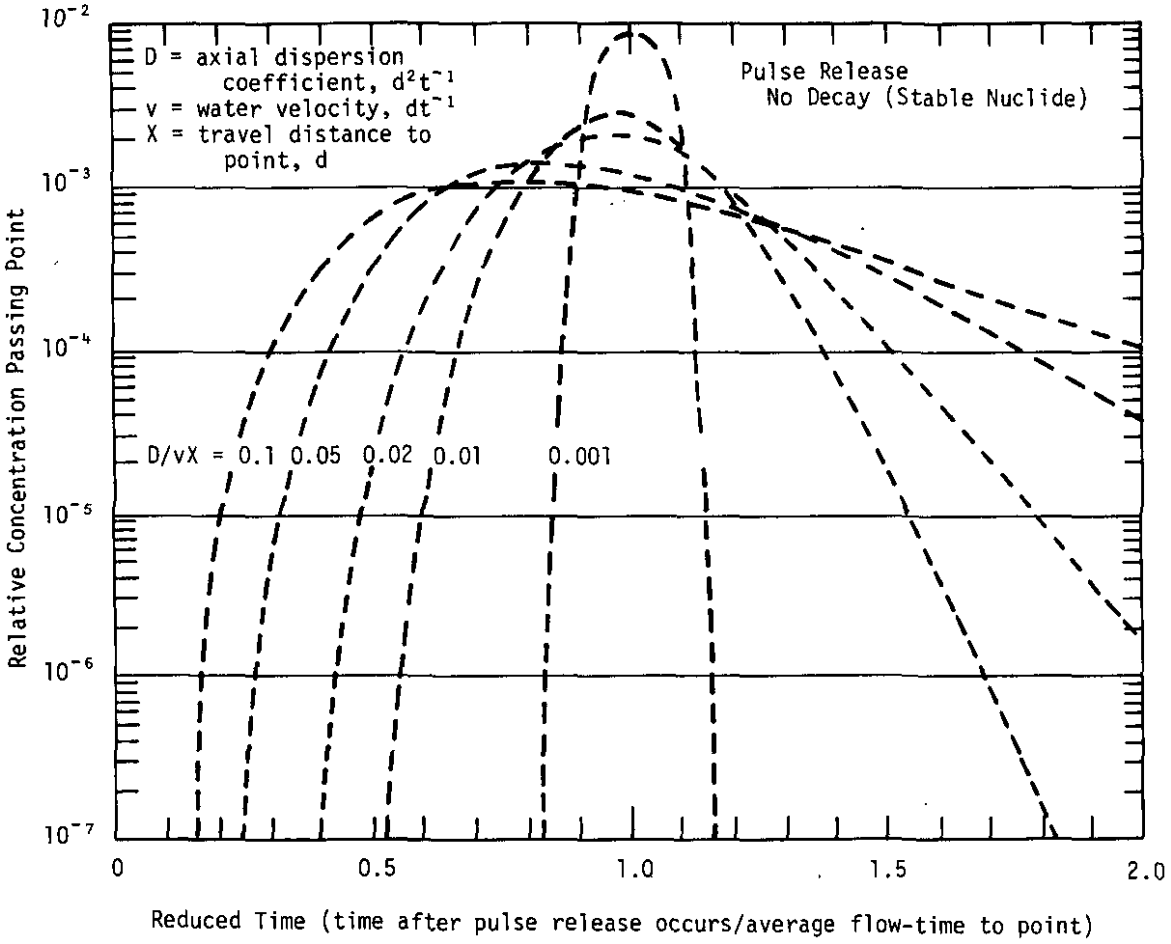

FIGURE 18. Pulse Release: Concentrations of Stable Nuclide Passing a Downstream Point Relative to Initial Concentration (for dispersion numbers, D/vX, of 0.1 to 0.001)

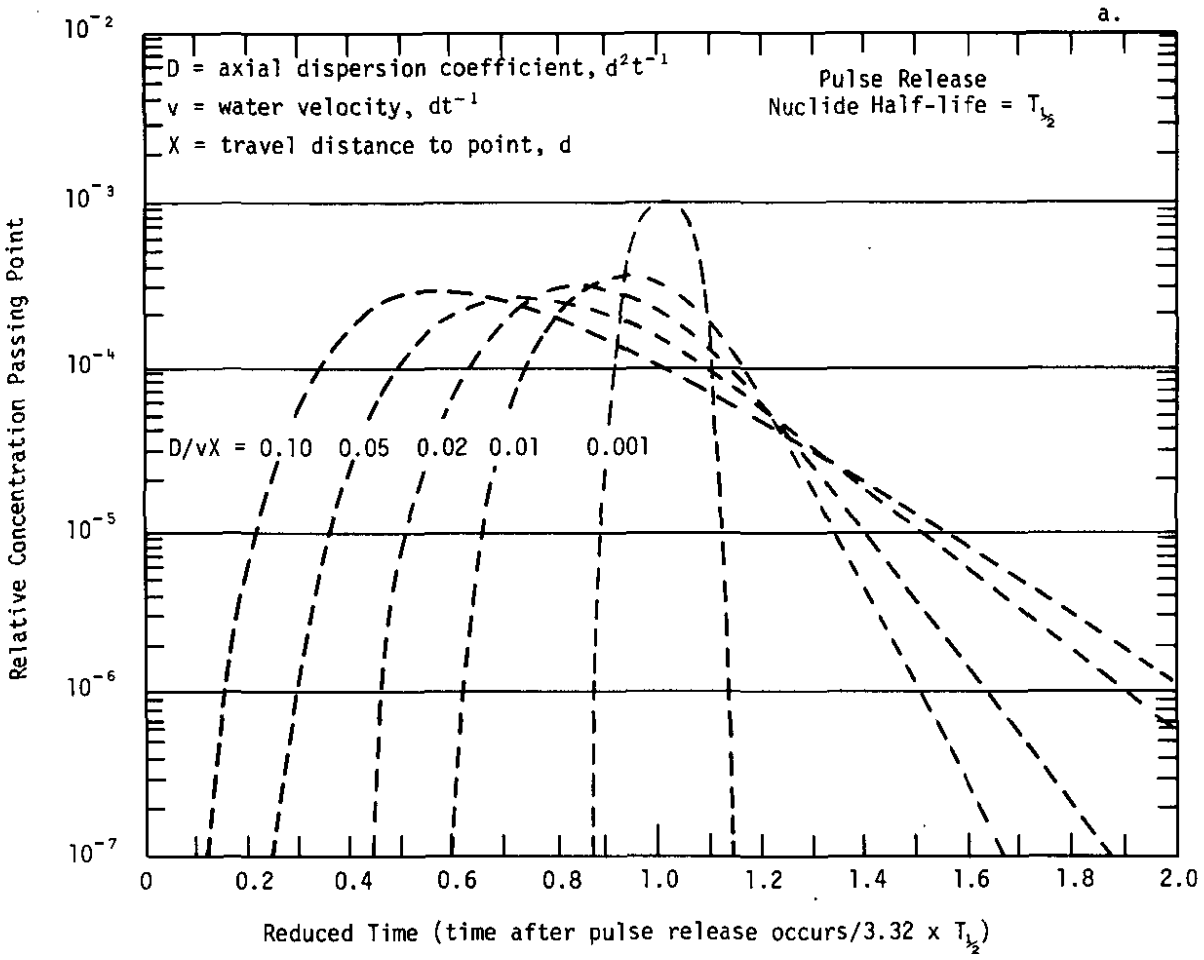

FIGURE 19a. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factors of 3.32 x $T_{1/2}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

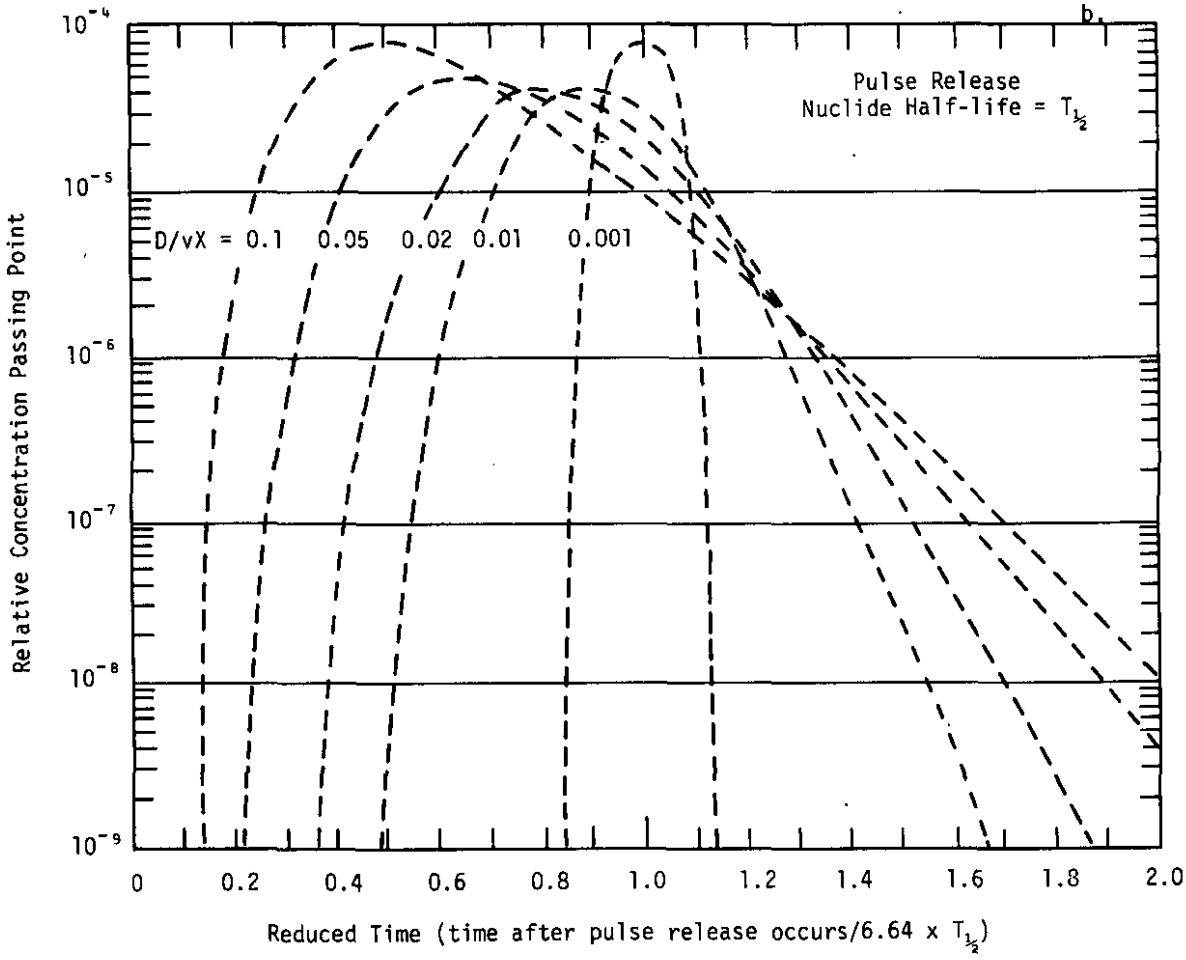

FIGURE 19b. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factors of 6.64 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

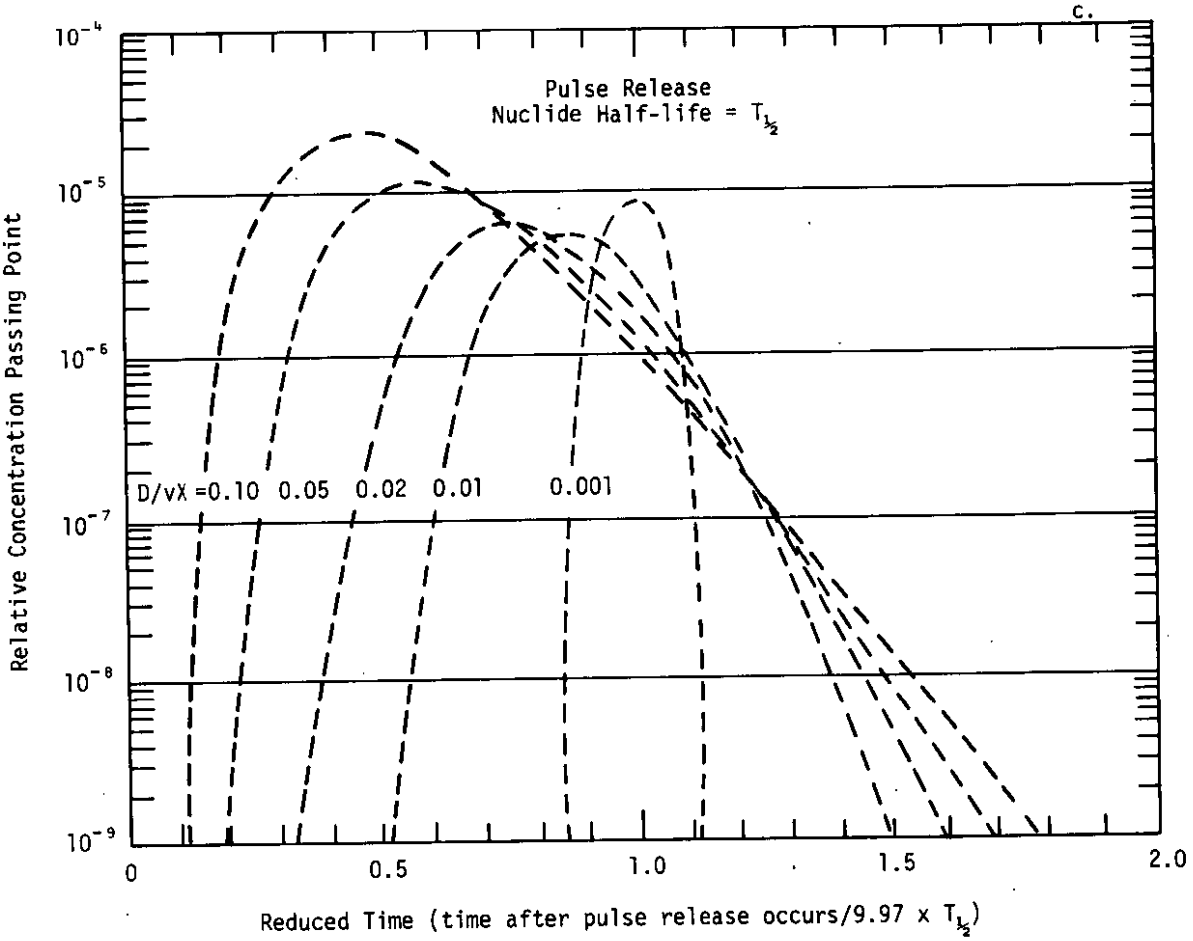

FIGURE 19c. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factors of 9.97 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

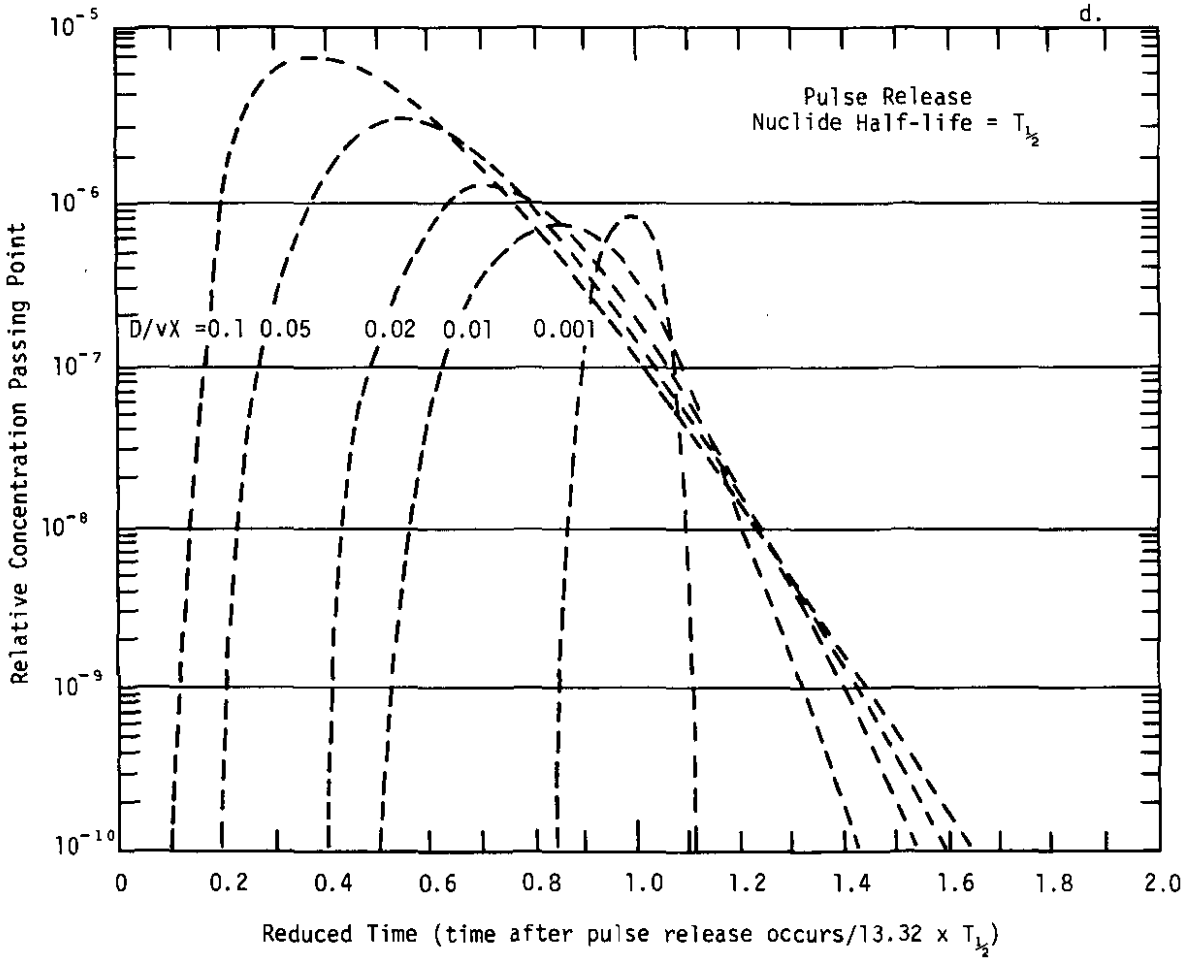

FIGURE 19d. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factors of 13.32 x $T_{1/2}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

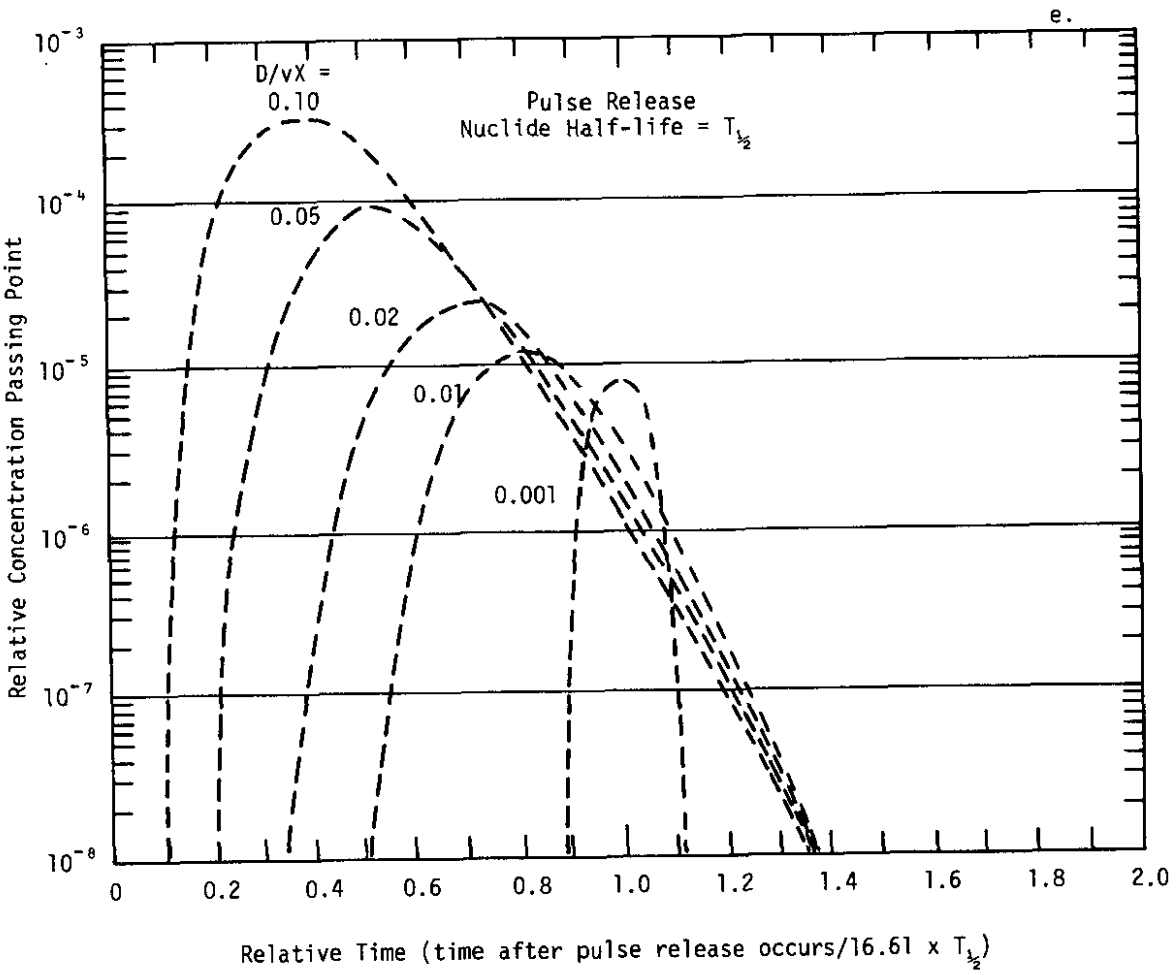

FIGURE 19e. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factors of 16.61 x $T_{1/2}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

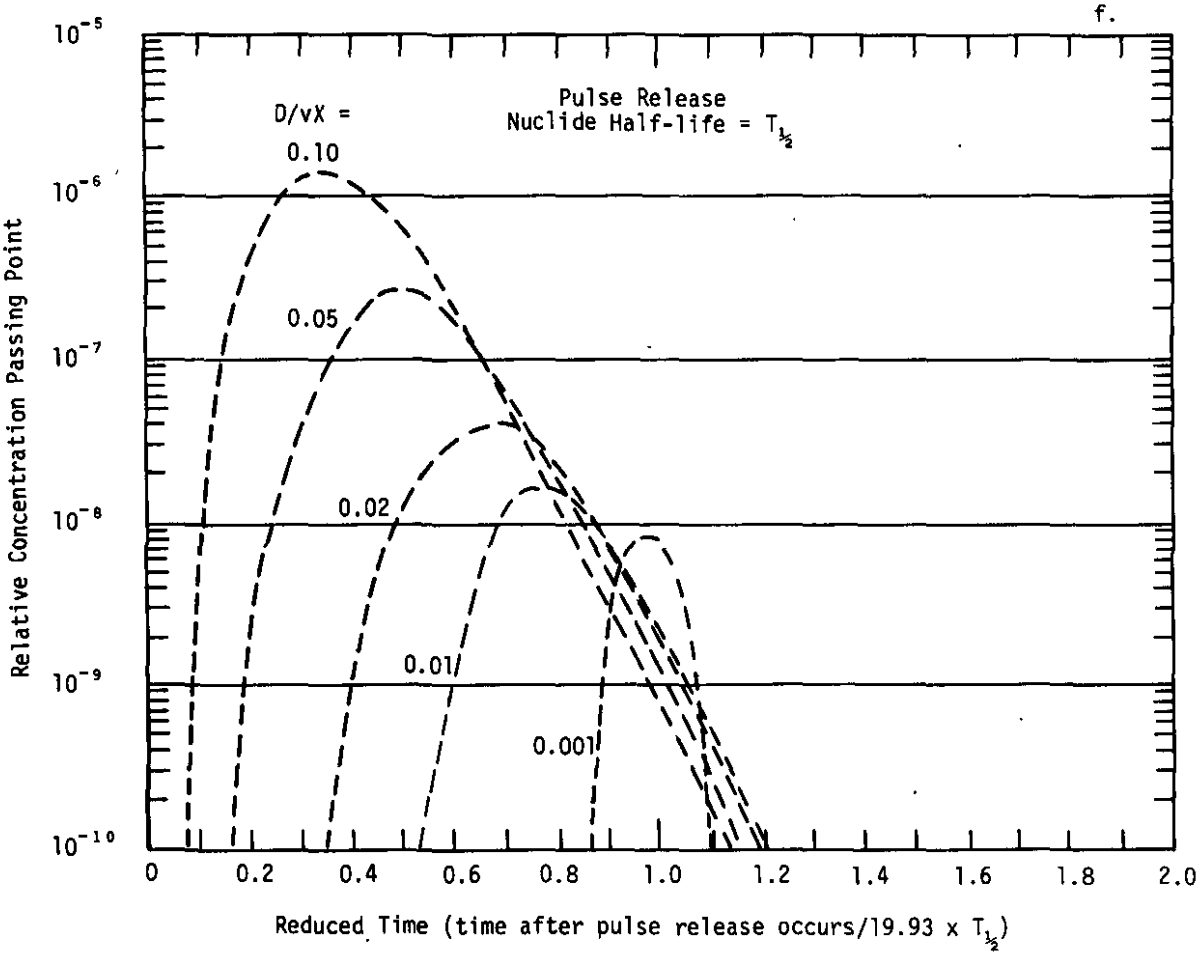

FIGURE 19f. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factors of 19.93 x $T_{1/2}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

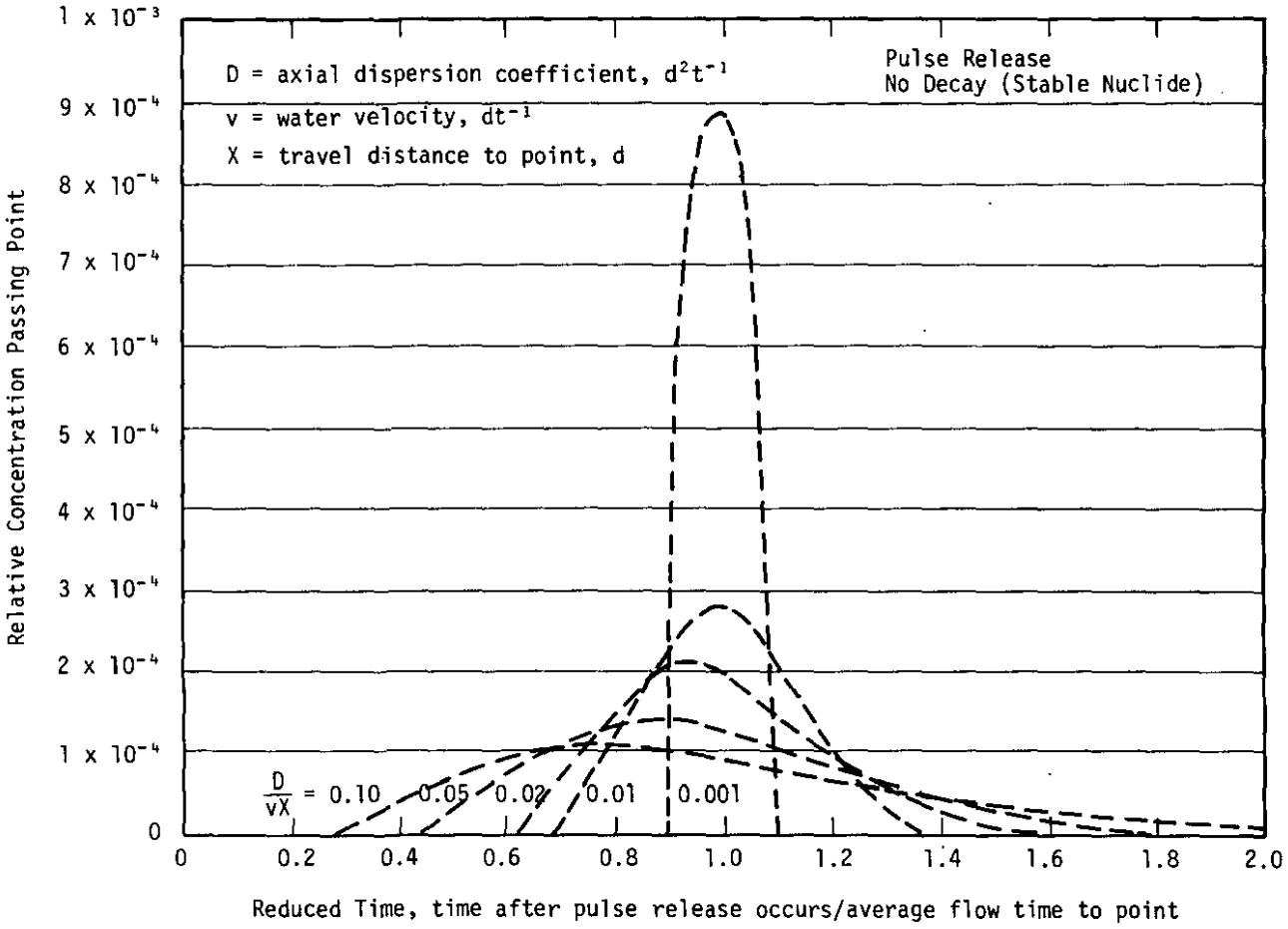

FIGURE 20. Pulse Release: Concentrations of Stable Nuclide Passing a Downstream Point Relative to Initial Concentration (similar to Figure 18, except the ordinate is linear rather than logarithmic)

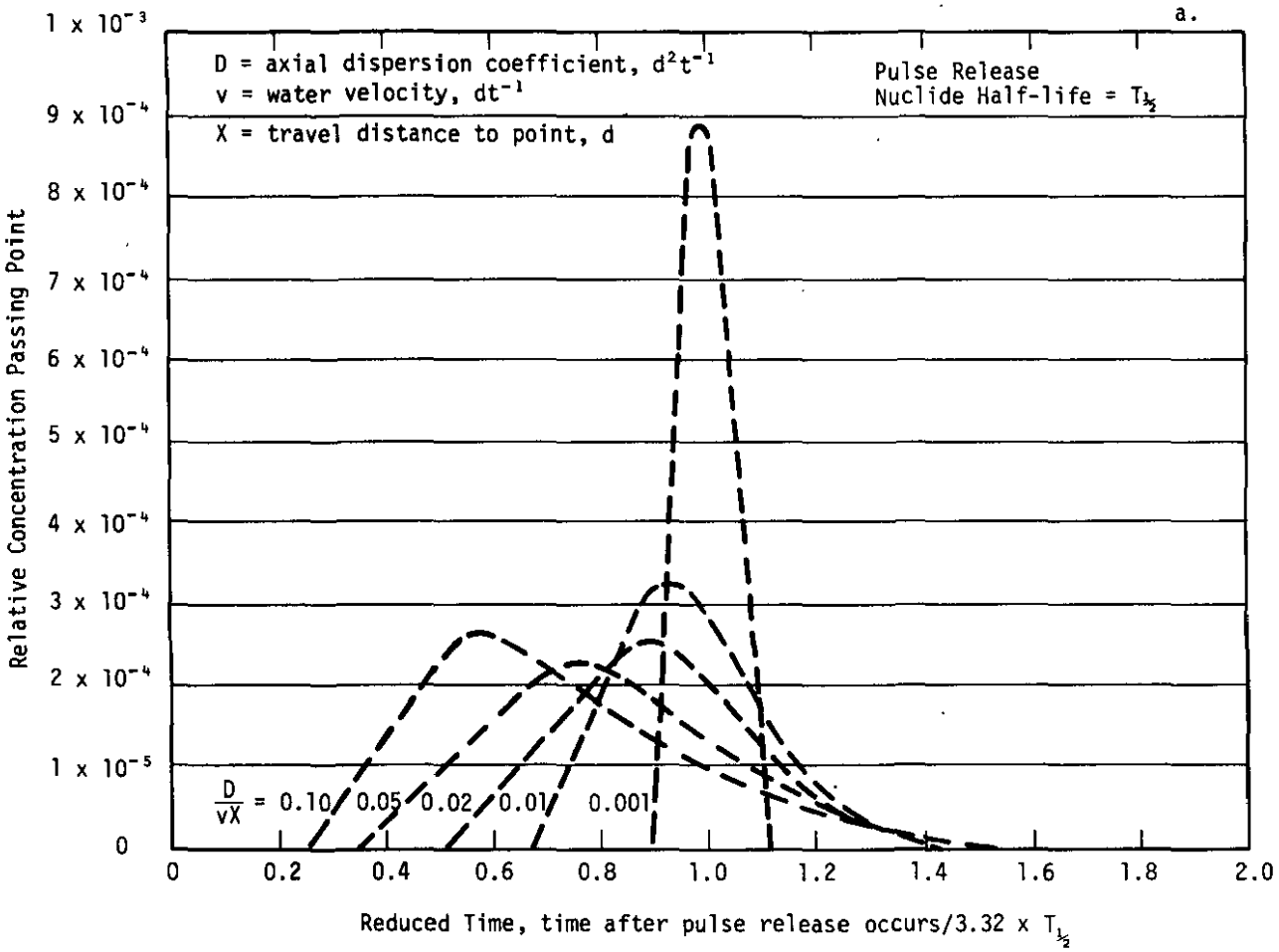

FIGURE 21a. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 19a, except the ordinate is linear rather than logarithmic)

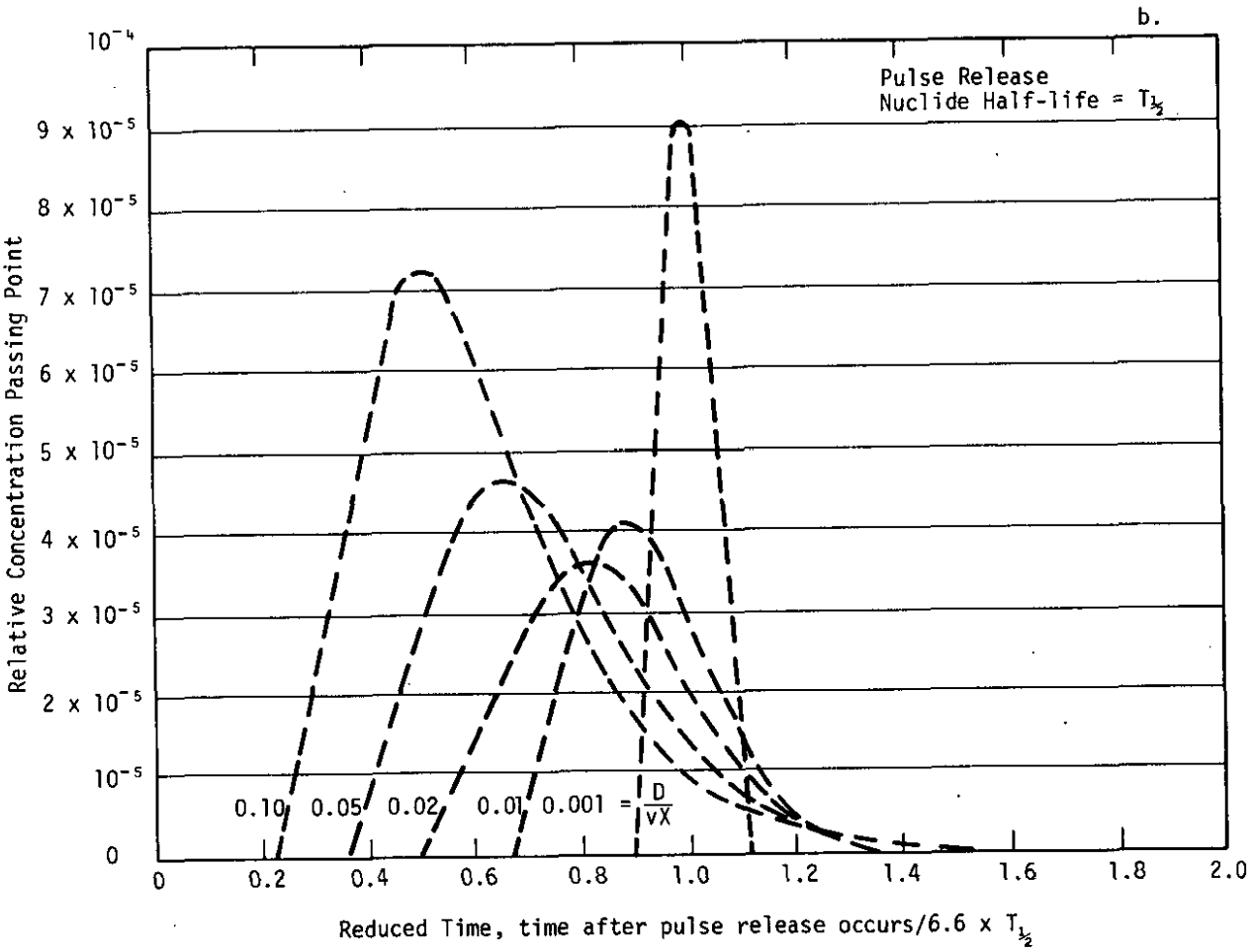

FIGURE 21b. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 19b, except the ordinate is linear rather than logarithmic)

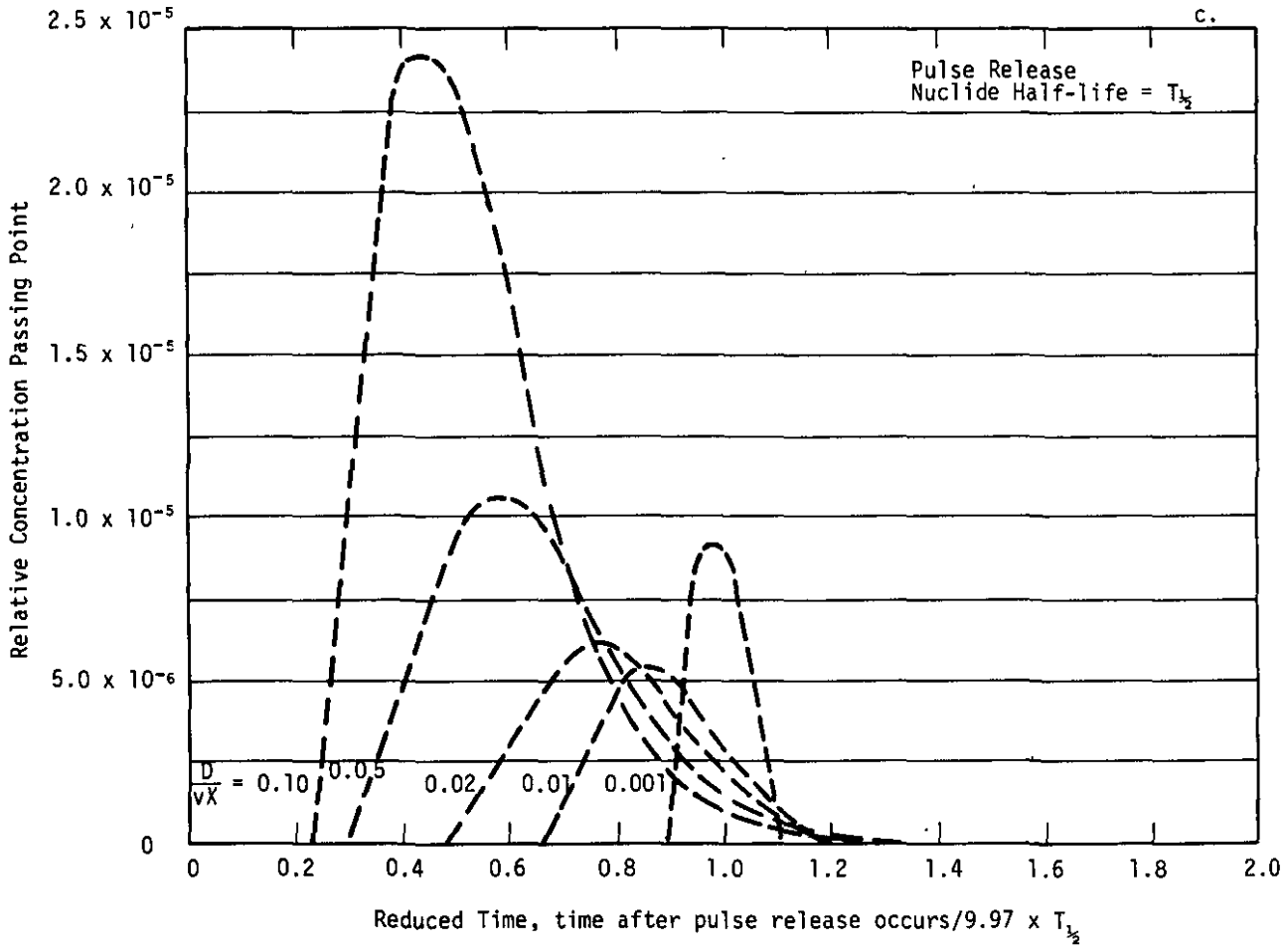

FIGURE 21c. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 19c, except the ordinate is linear rather than logarithmic)

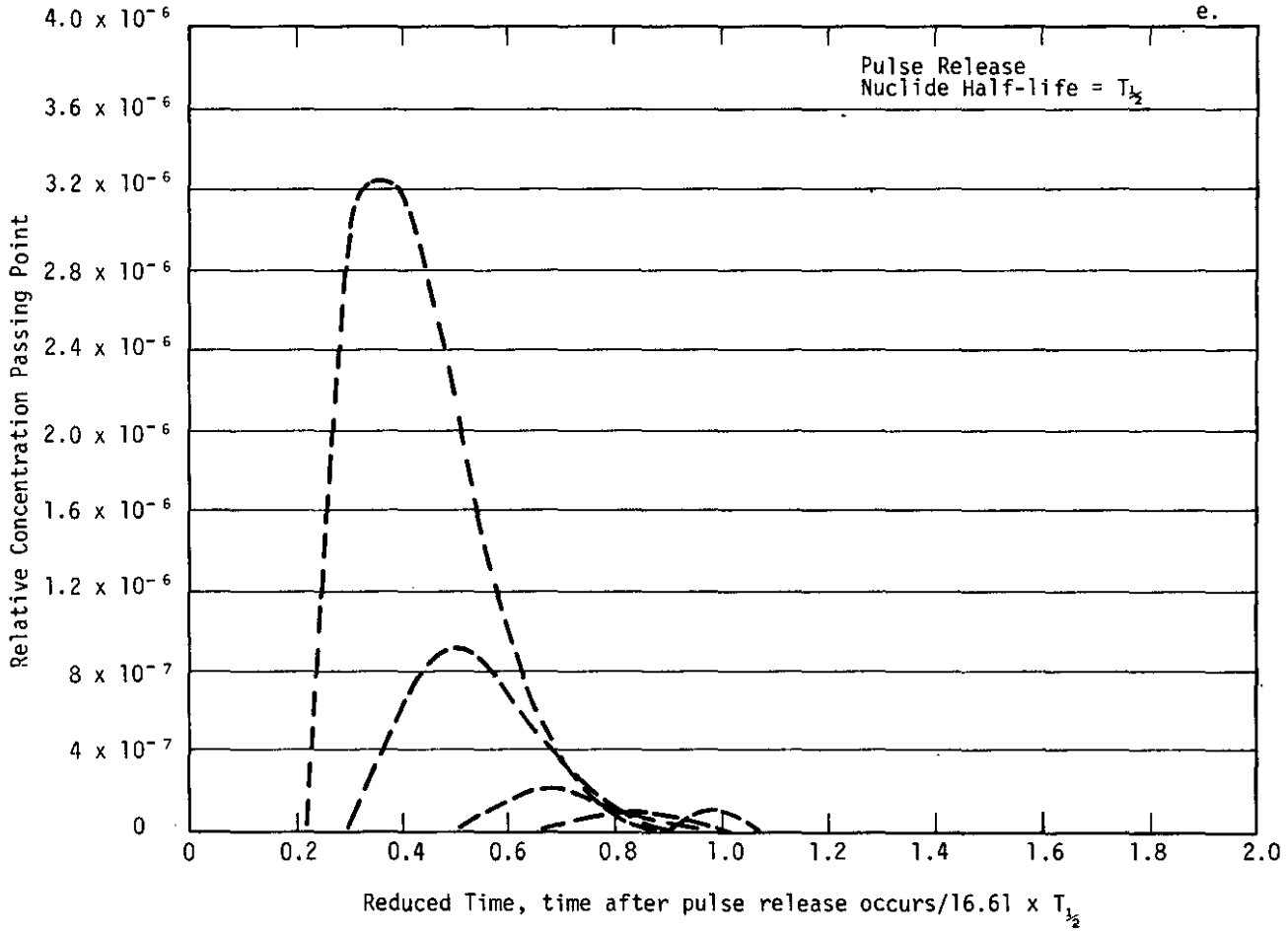

FIGURE 21e. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 19e, except the ordinate is linear rather than logarithmic)

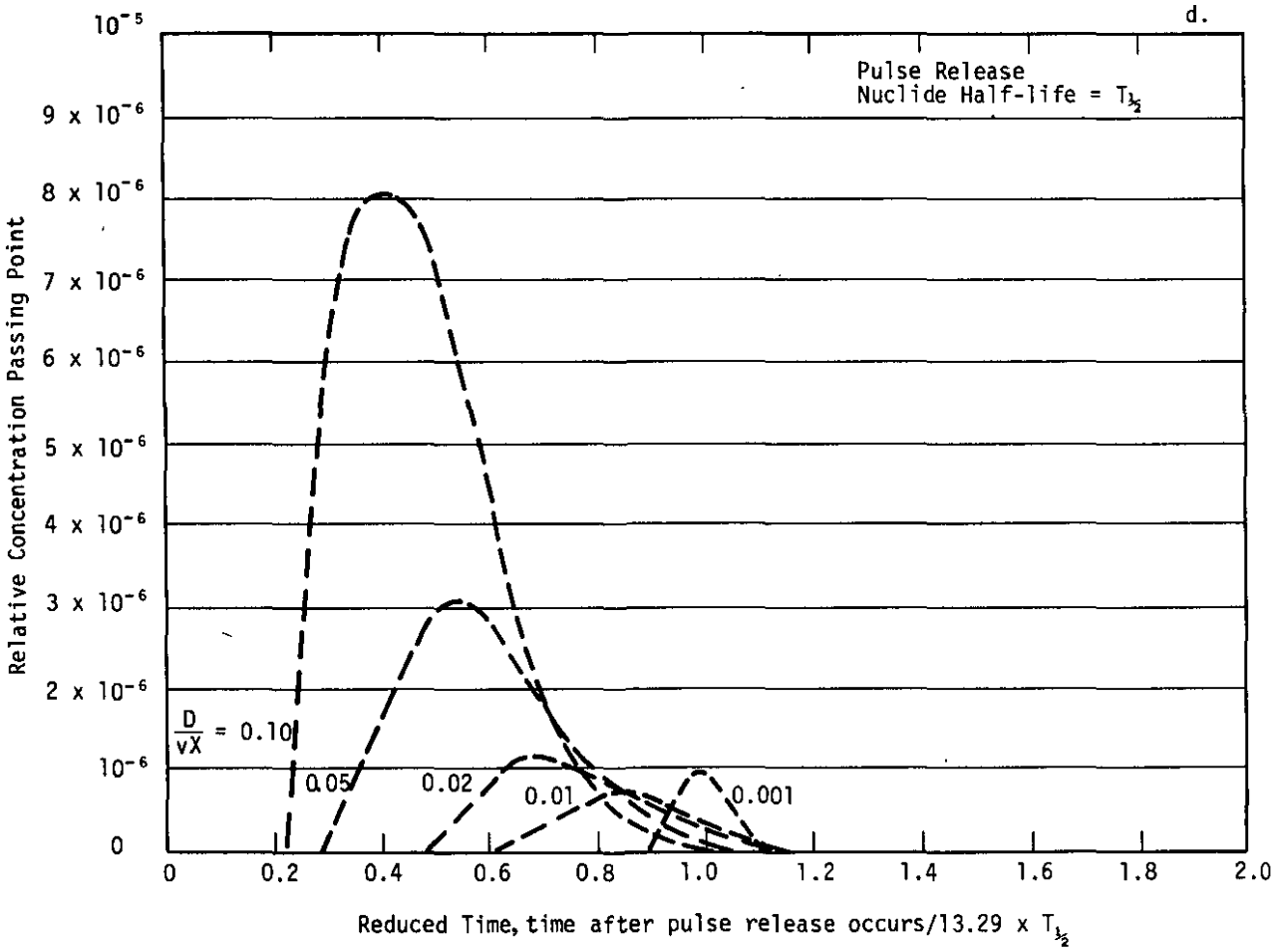

FIGURE 21d. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 19d, except the ordinate is linear rather than logarithmic)

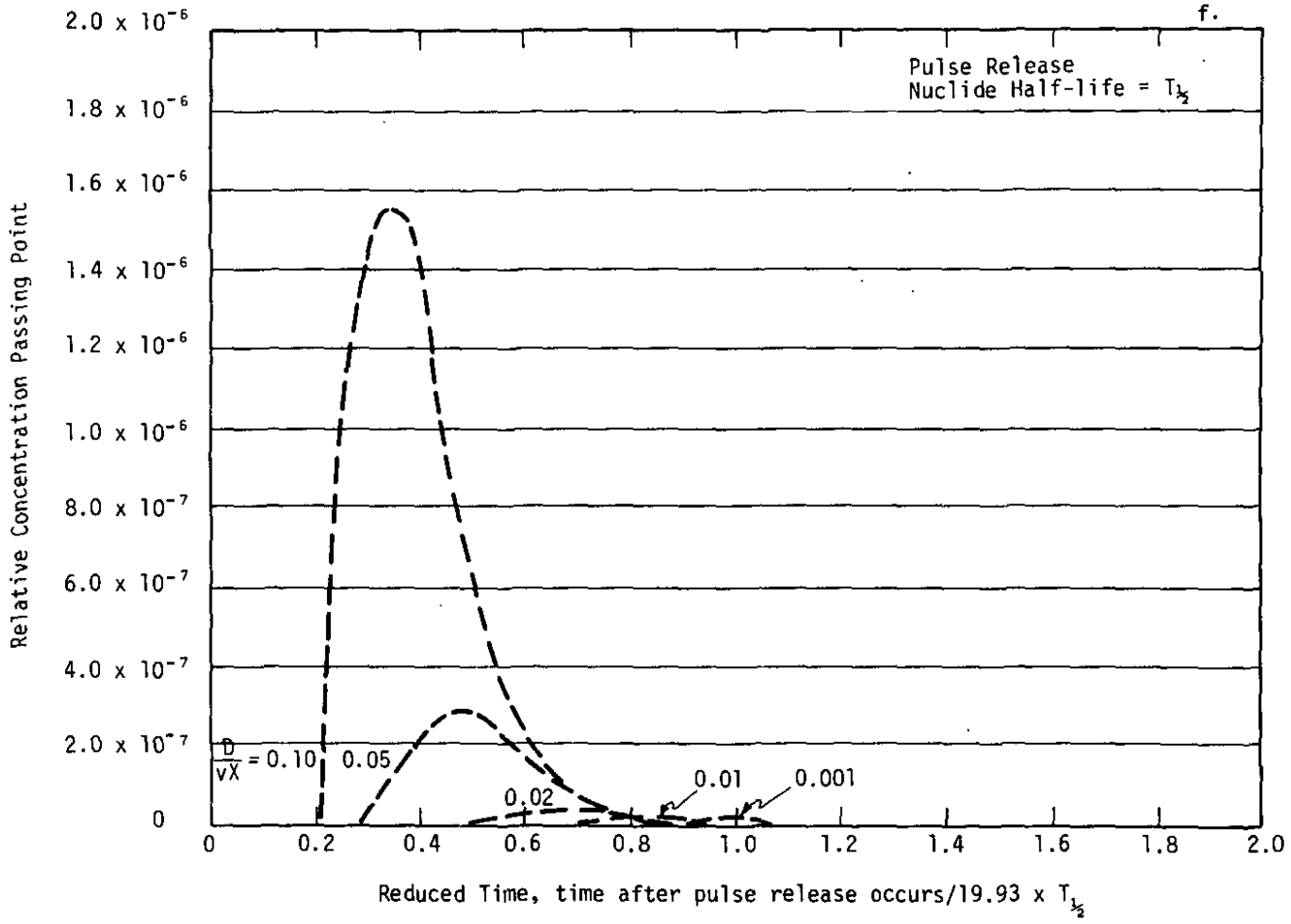

FIGURE 21f. Pulse Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 19f, except the ordinate is linear rather than logarithmic)

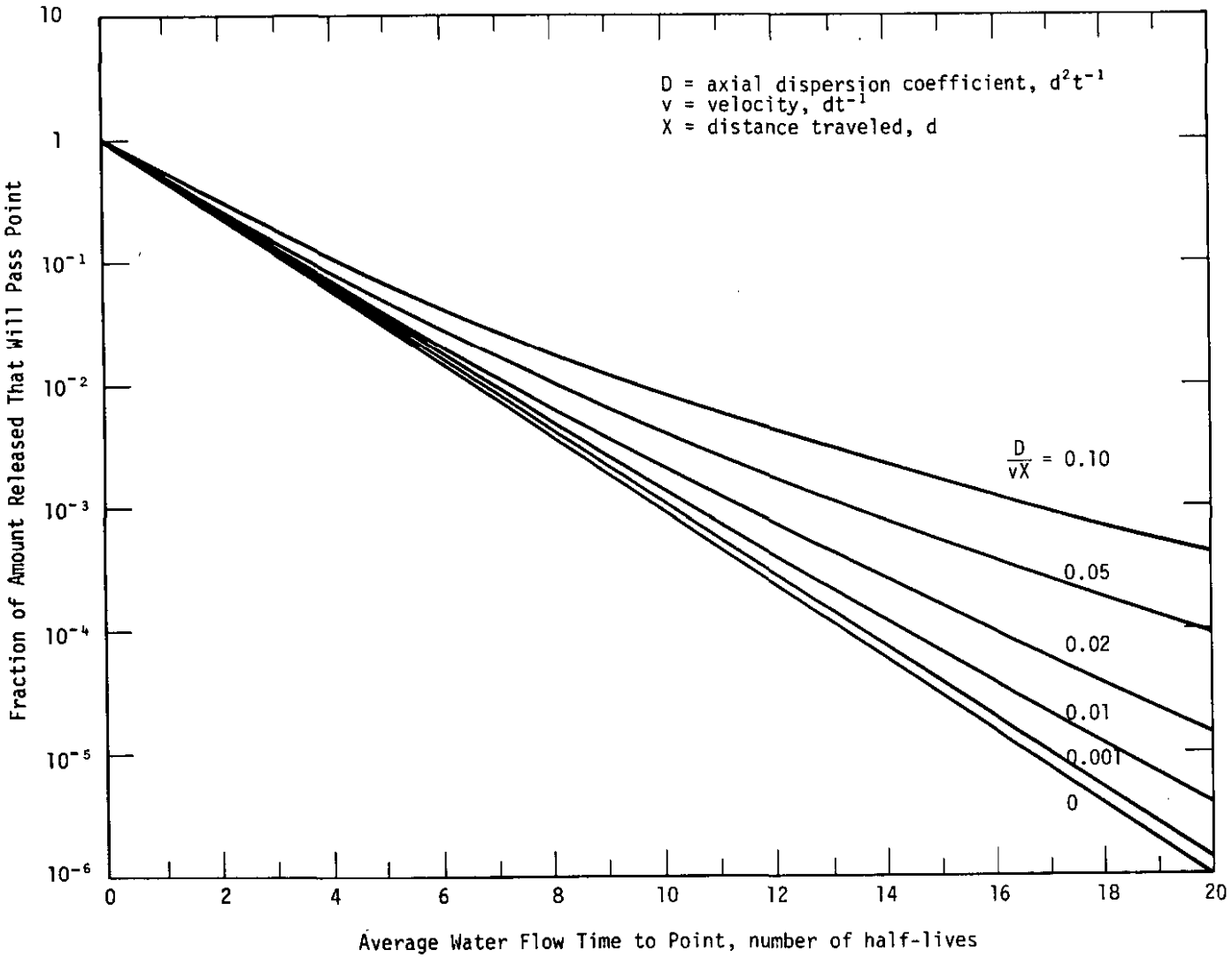

FIGURE 22. Pulse Release: Fraction of Released Radionuclide Passing a Downstream Point as a Function of Dispersion Numbers and of Decay Time

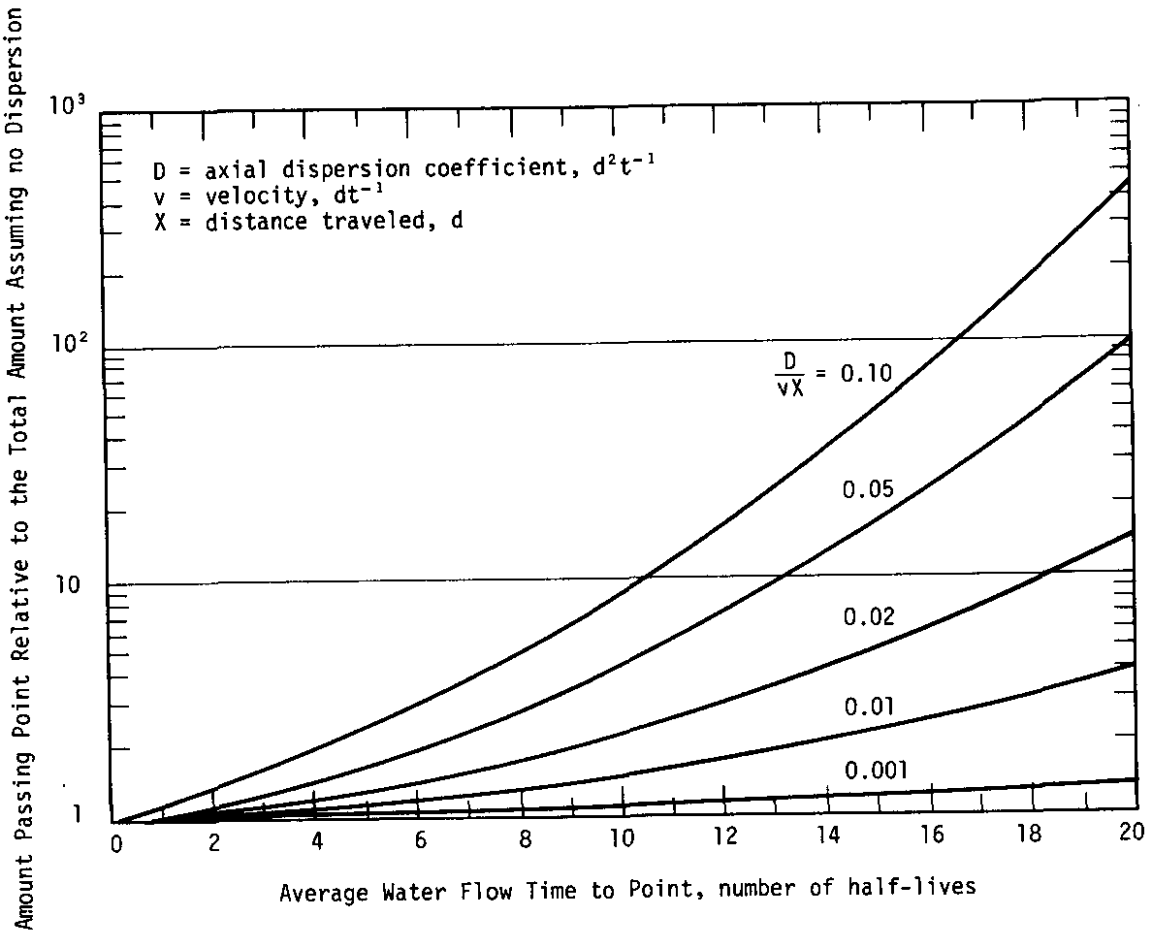

FIGURE 23. Pulse Release: Relative Amount of Released Radionuclide Passing a Downstream Point as a Function of Dispersion Number and of Decay Time

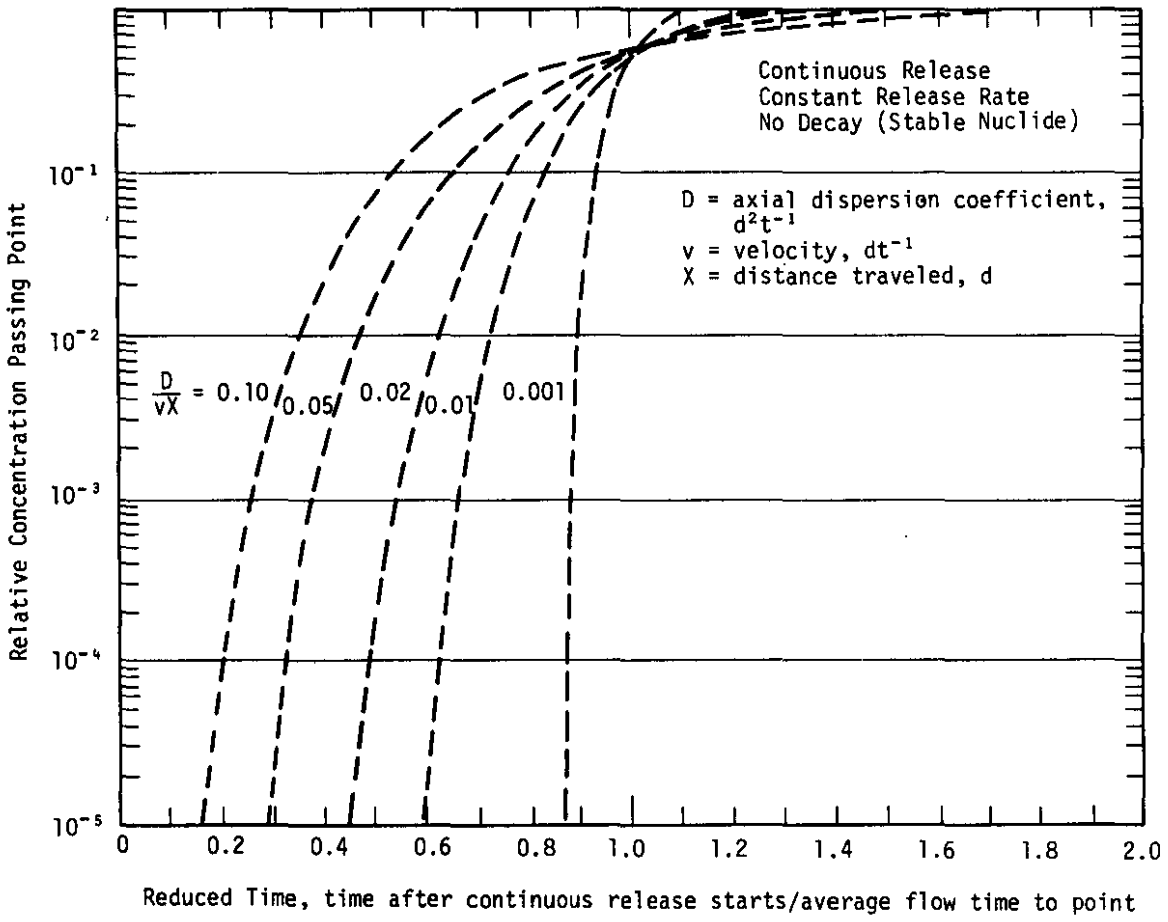

FIGURE 24. Continuous Release: Concentrations of Stable Nuclide Passing a Downstream Point Relative to Initial Concentration (for dispersion numbers, D/vX, of 0.1 to 0.001)

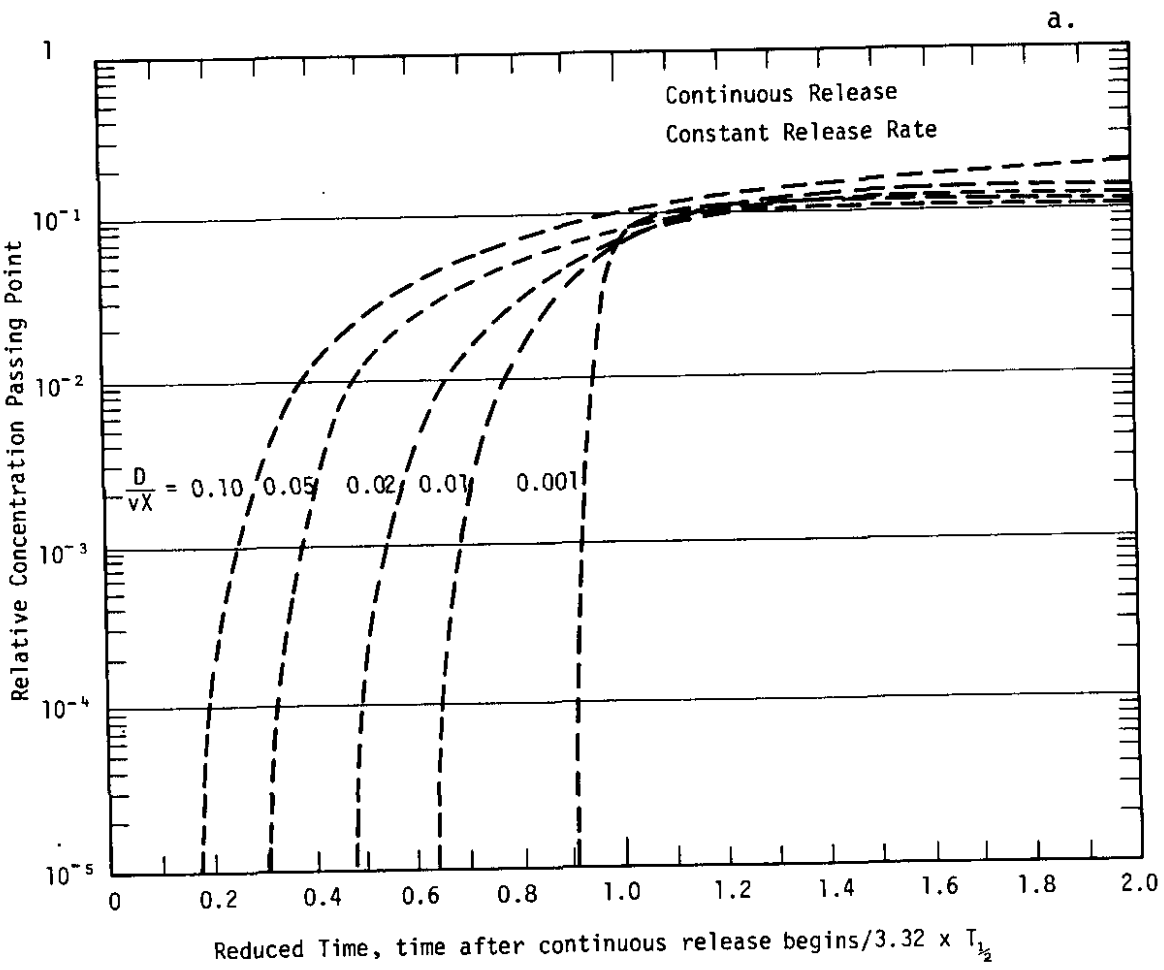

FIGURE 25a. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 3.32 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

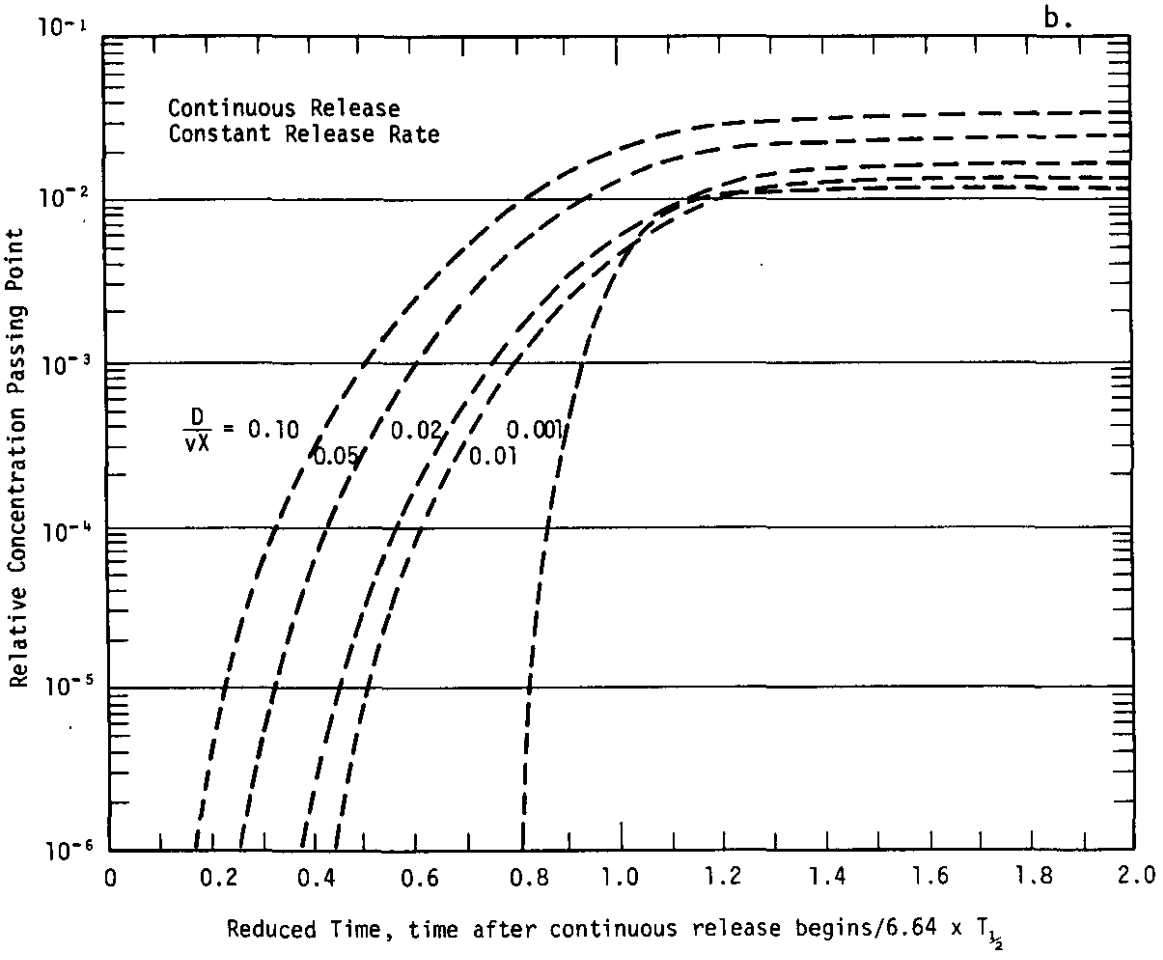

FIGURE 25b. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 6.64 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

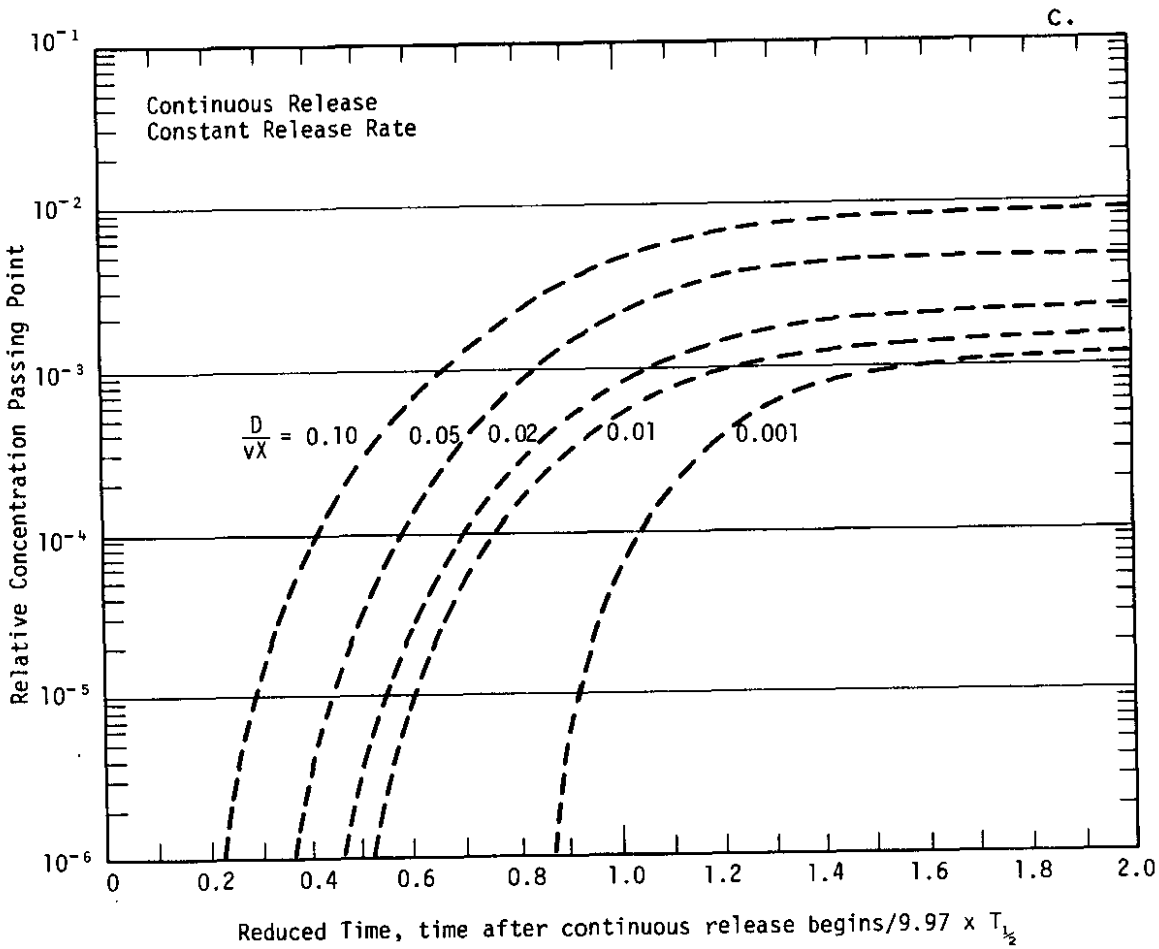

FIGURE 25c. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 9.97 x $T_{1/2}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

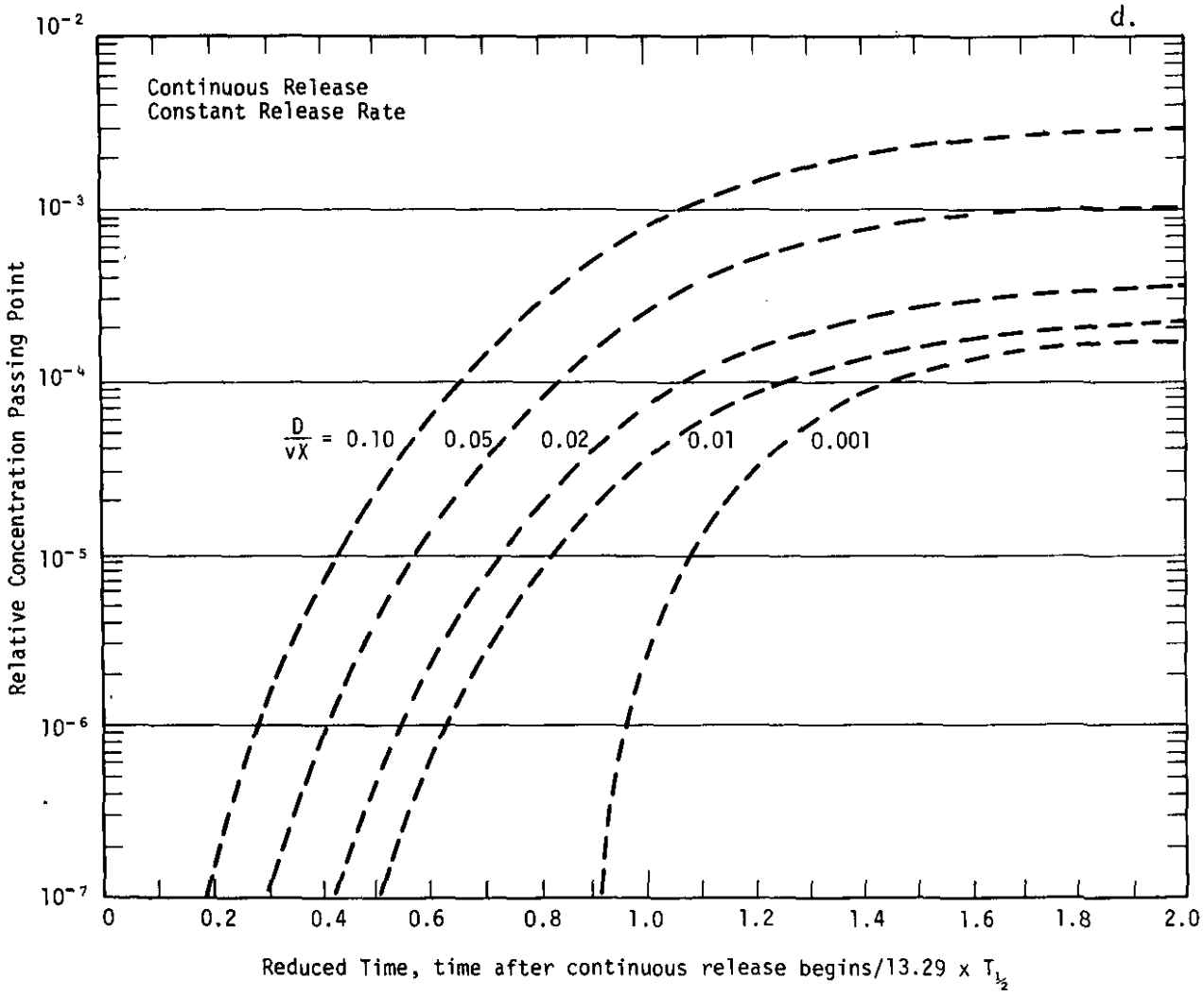

FIGURE 25d. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 13.29 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

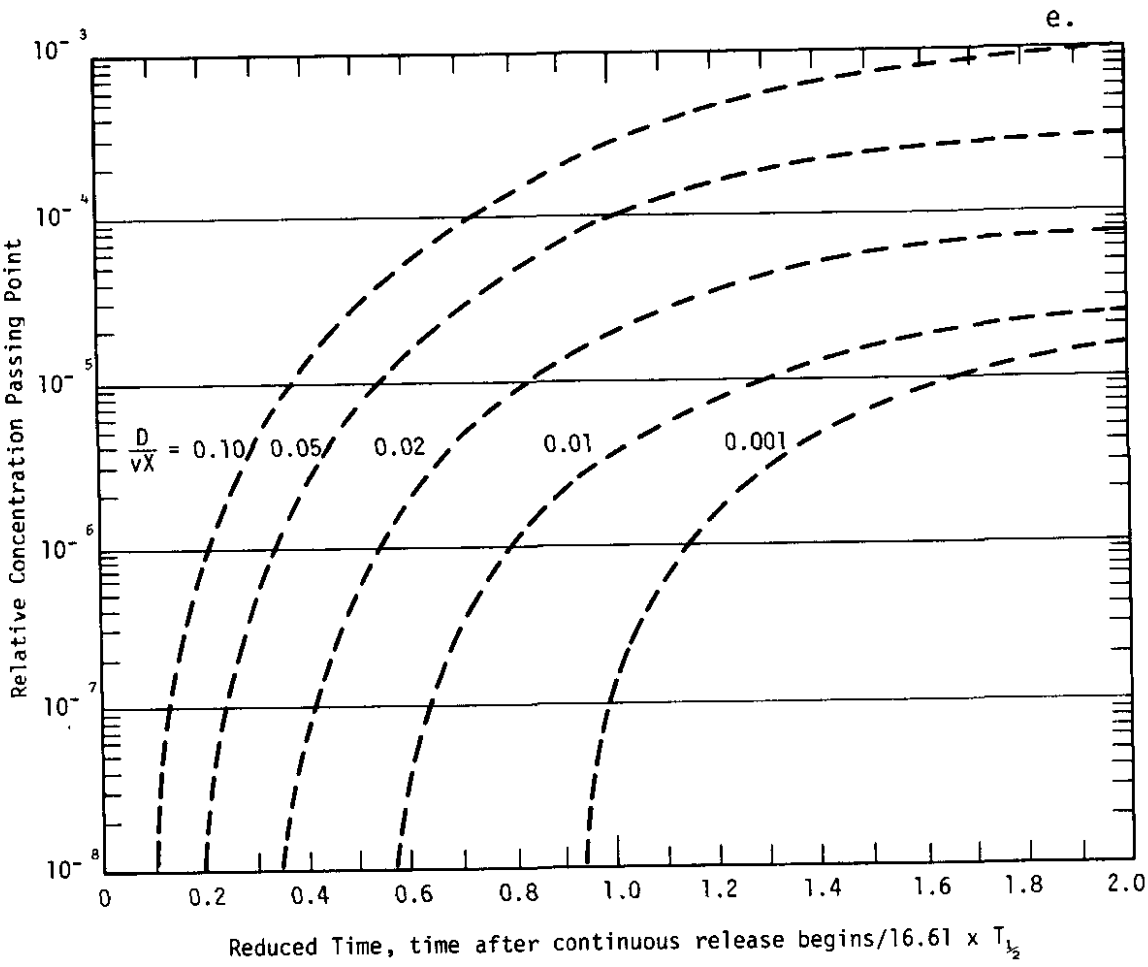

FIGURE 25e. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 16.61 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

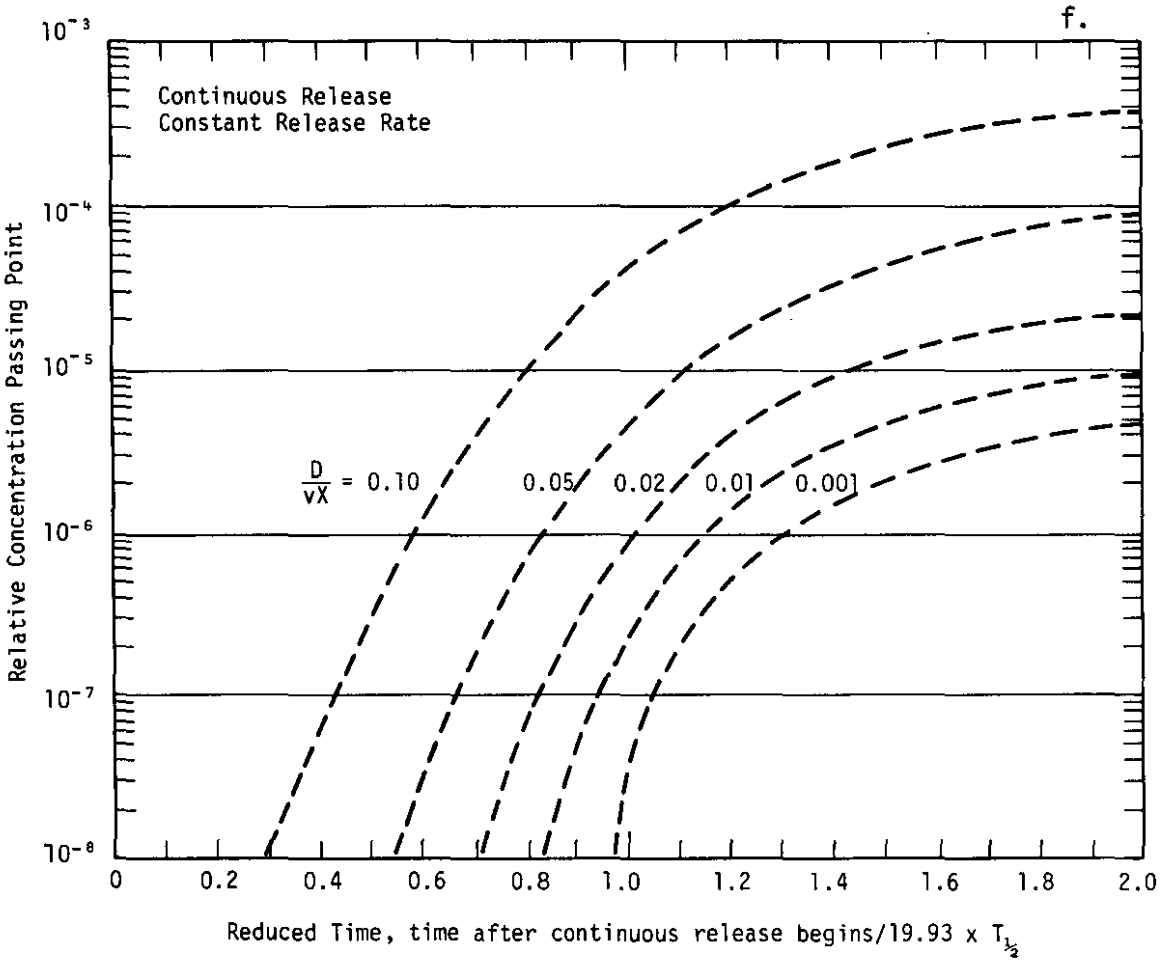

FIGURE 25f. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 19.93 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.1 to 0.001)

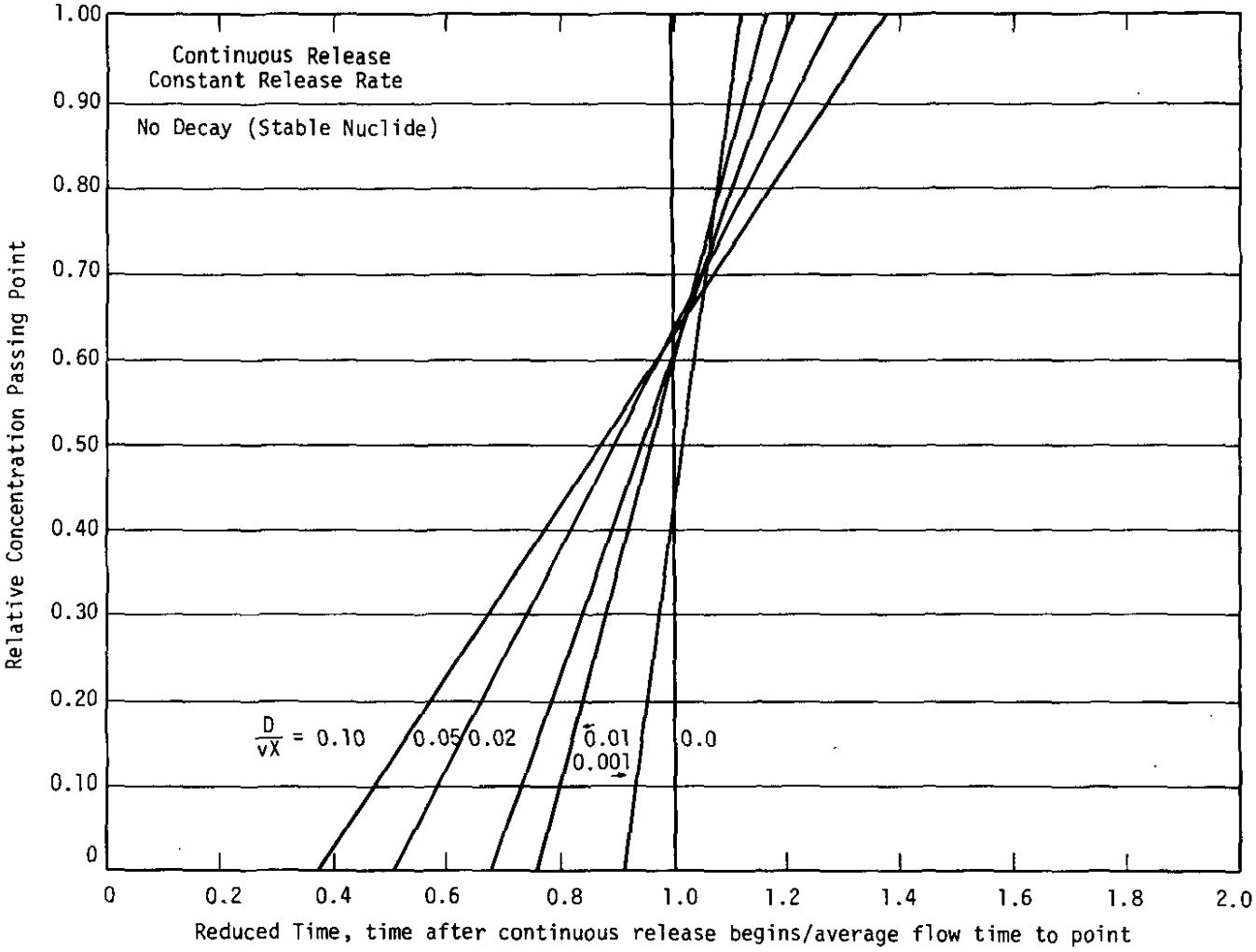

FIGURE 26. Continuous Release: Concentrations of Stable Nuclide Passing a Downstream Point Relative to Initial Concentration (similar to Figure 24, except the ordinate is linear rather than logarithmic)

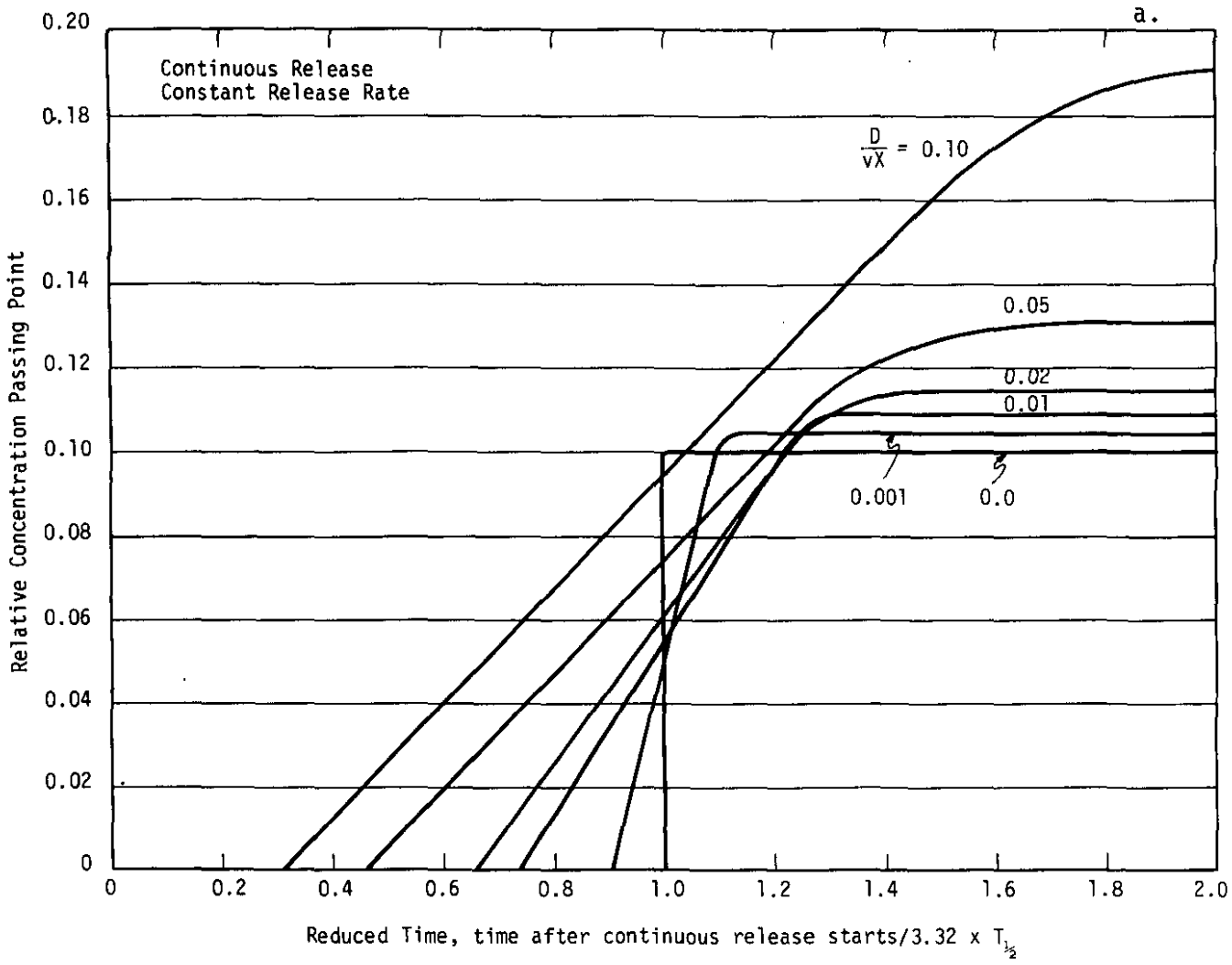

FIGURE 27a. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 25a, except the ordinate is linear rather than logarithmic)

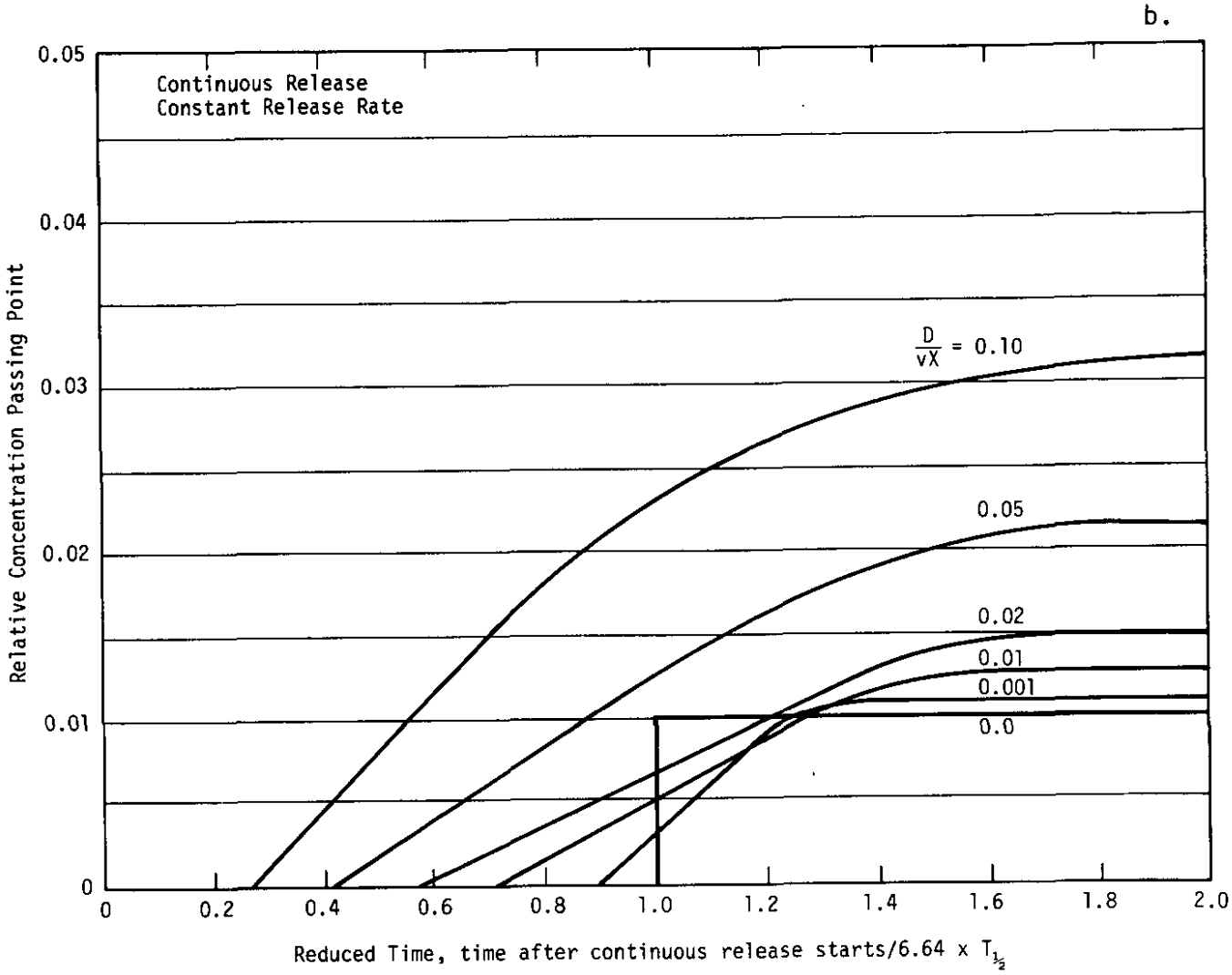

FIGURE 27b. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 25b, except the ordinate is linear rather than logarithmic)

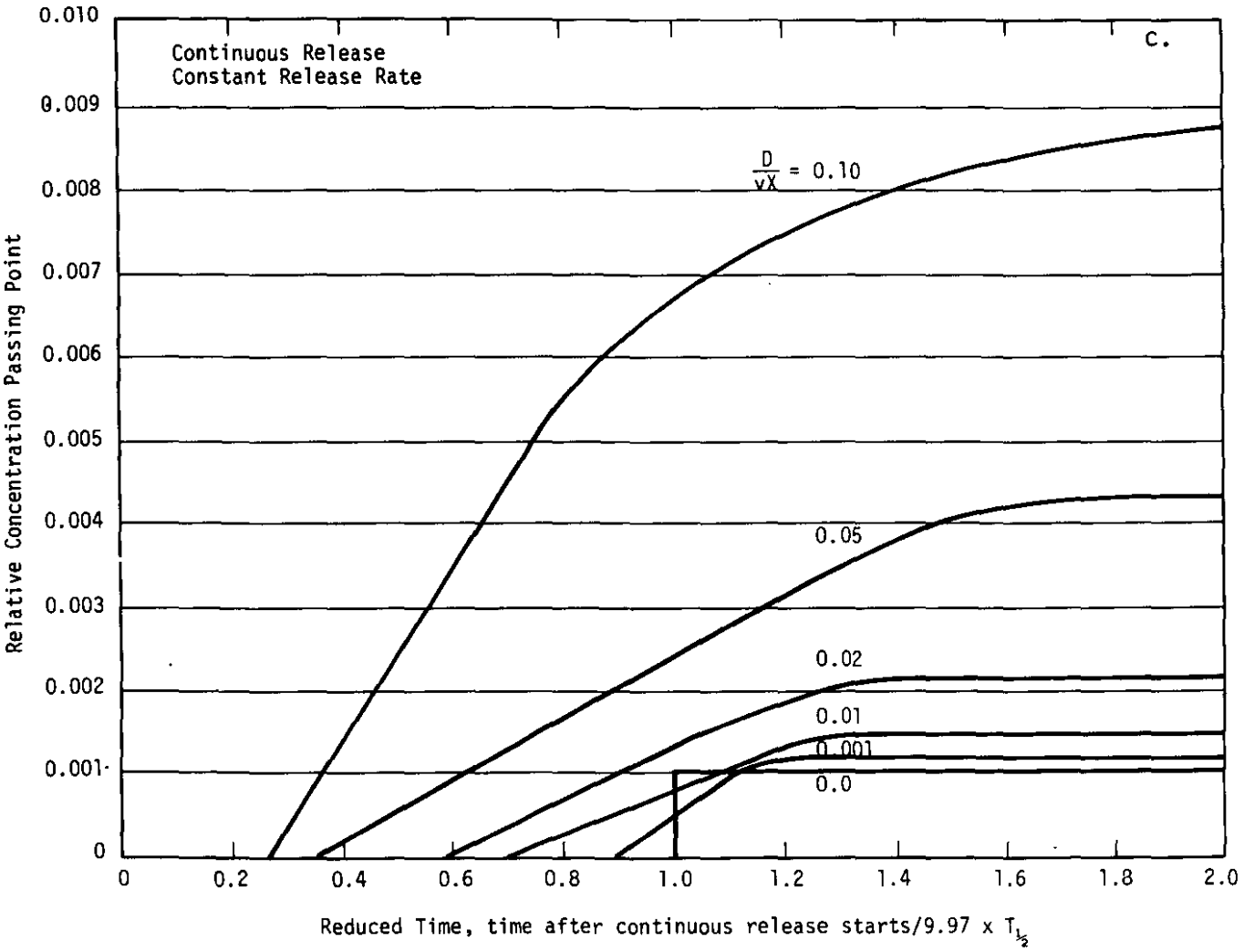

FIGURE 27c. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 25c, except the ordinate is linear rather than logarithmic)

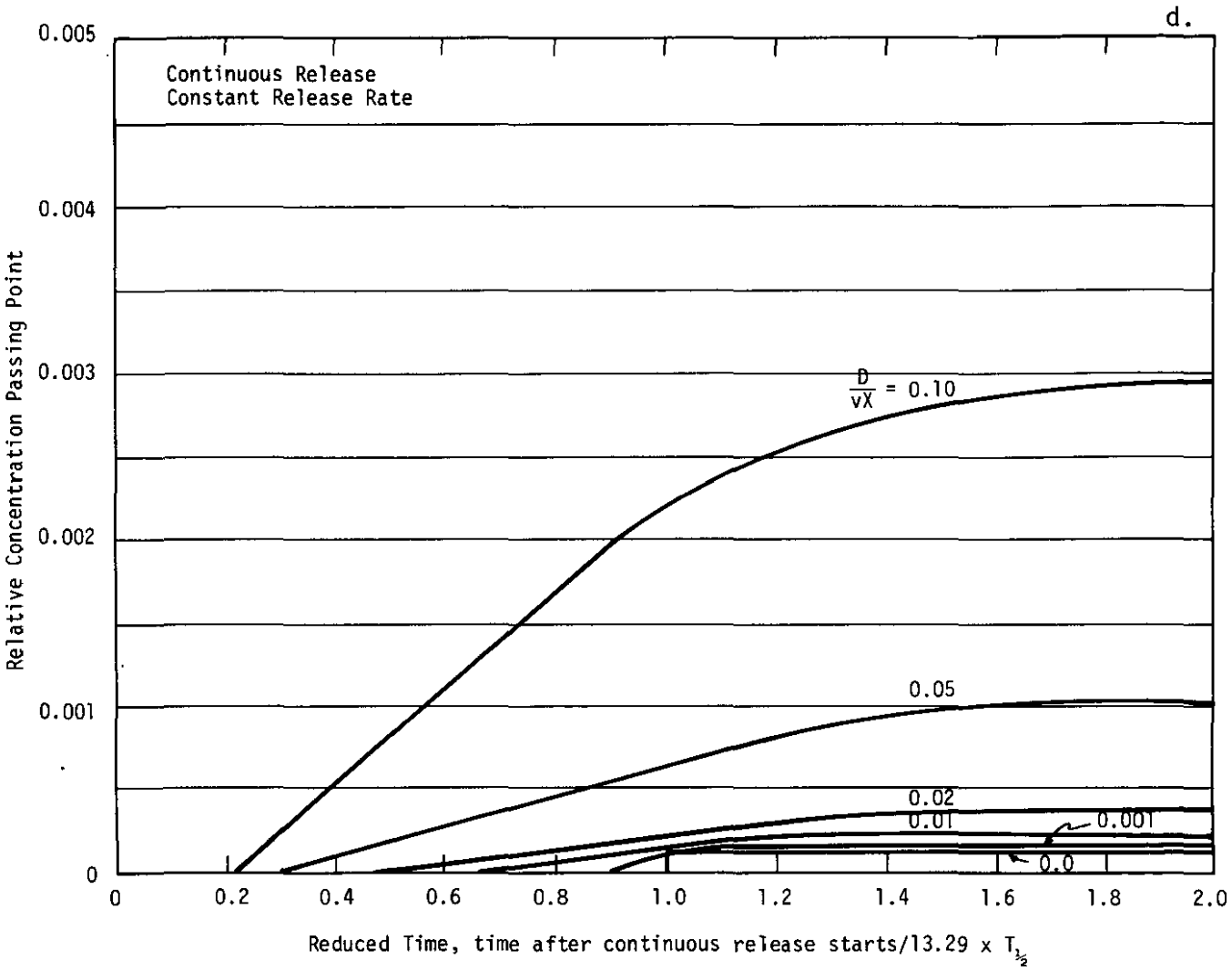

FIGURE 27d. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 25d, except the ordinate is linear rather than logarithmic)

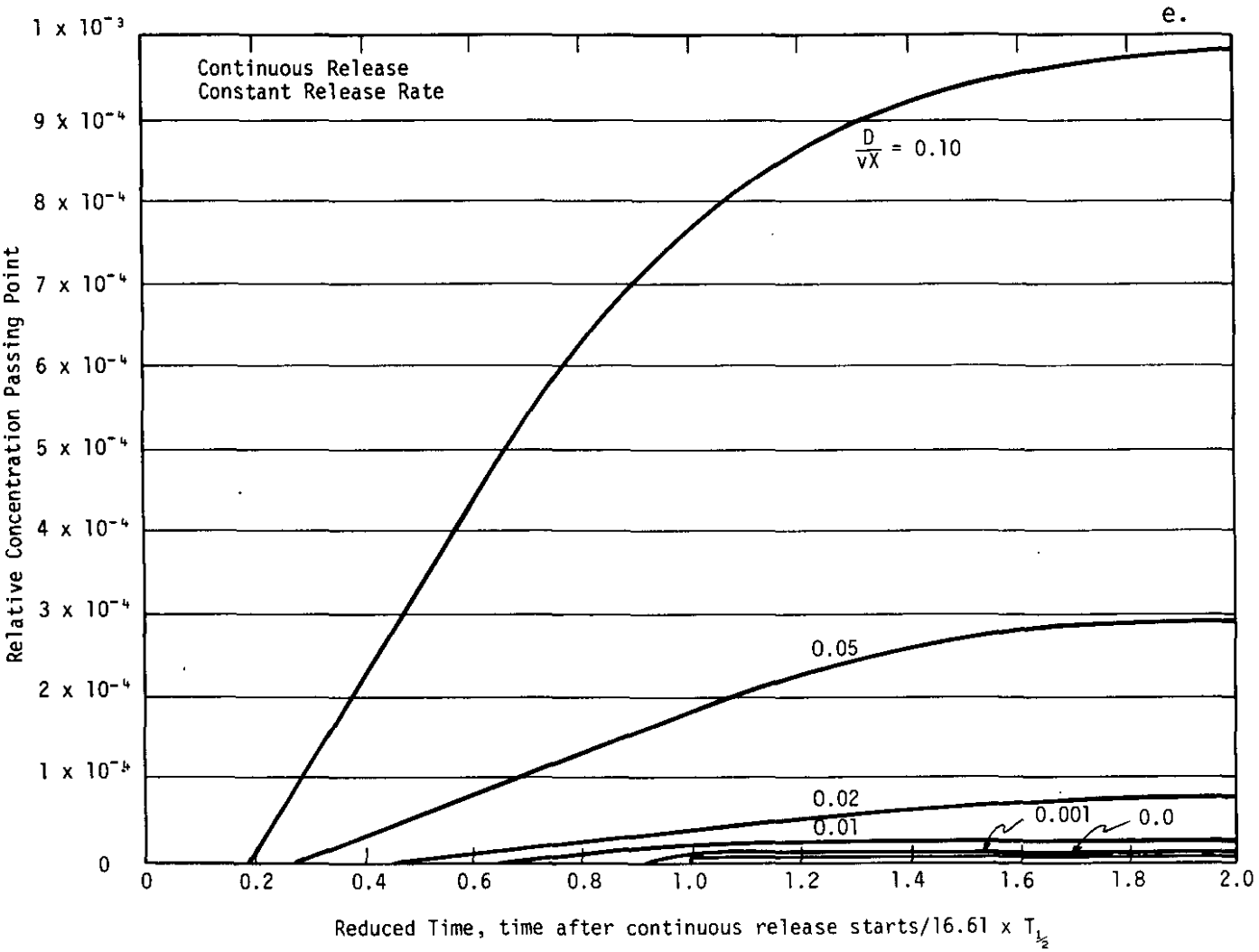

FIGURE 27e. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 25e, except the ordinate is linear rather than logarithmic)

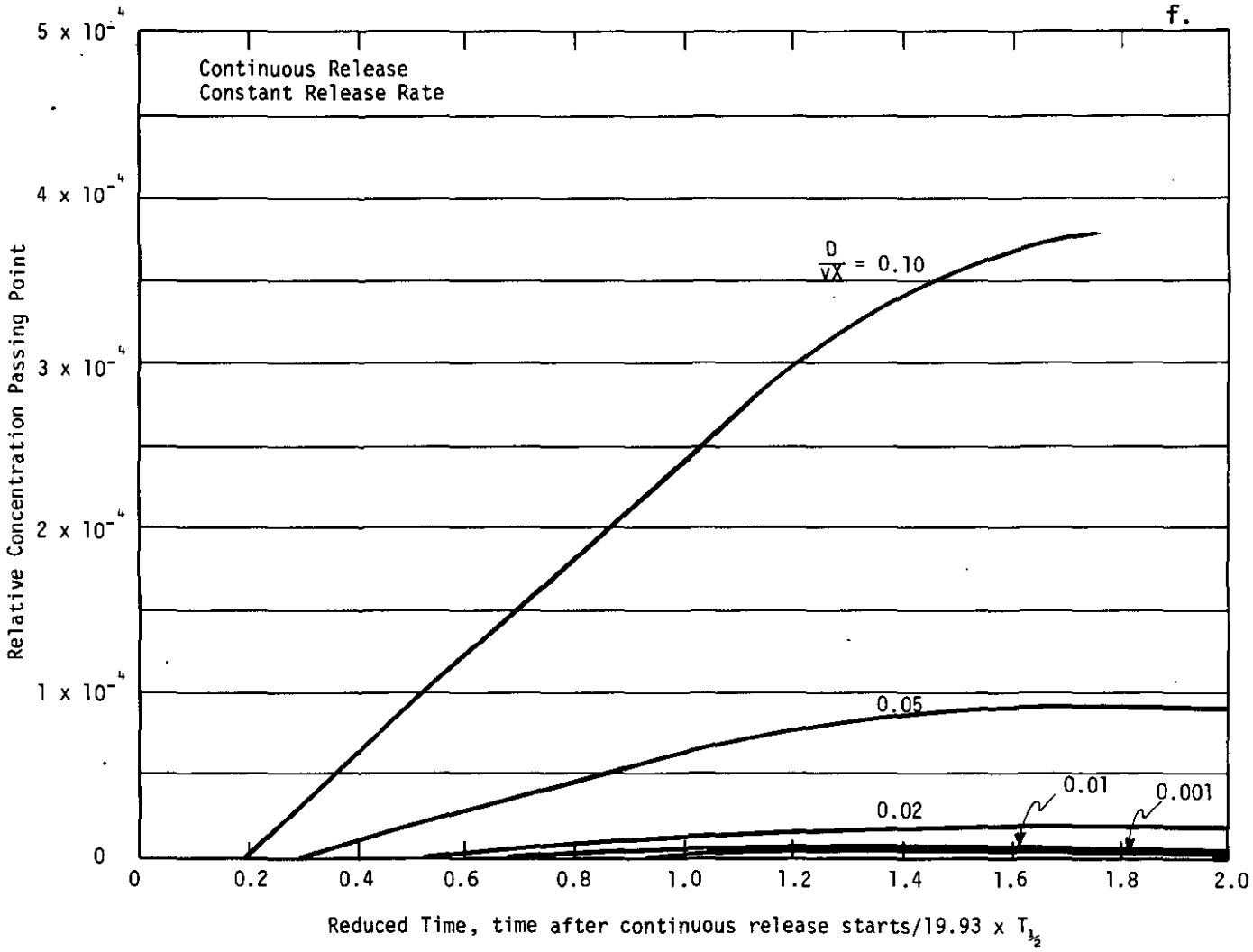

FIGURE 27f. Continuous Release: Concentrations of Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 25f, except the ordinate is linear rather than logarithmic)

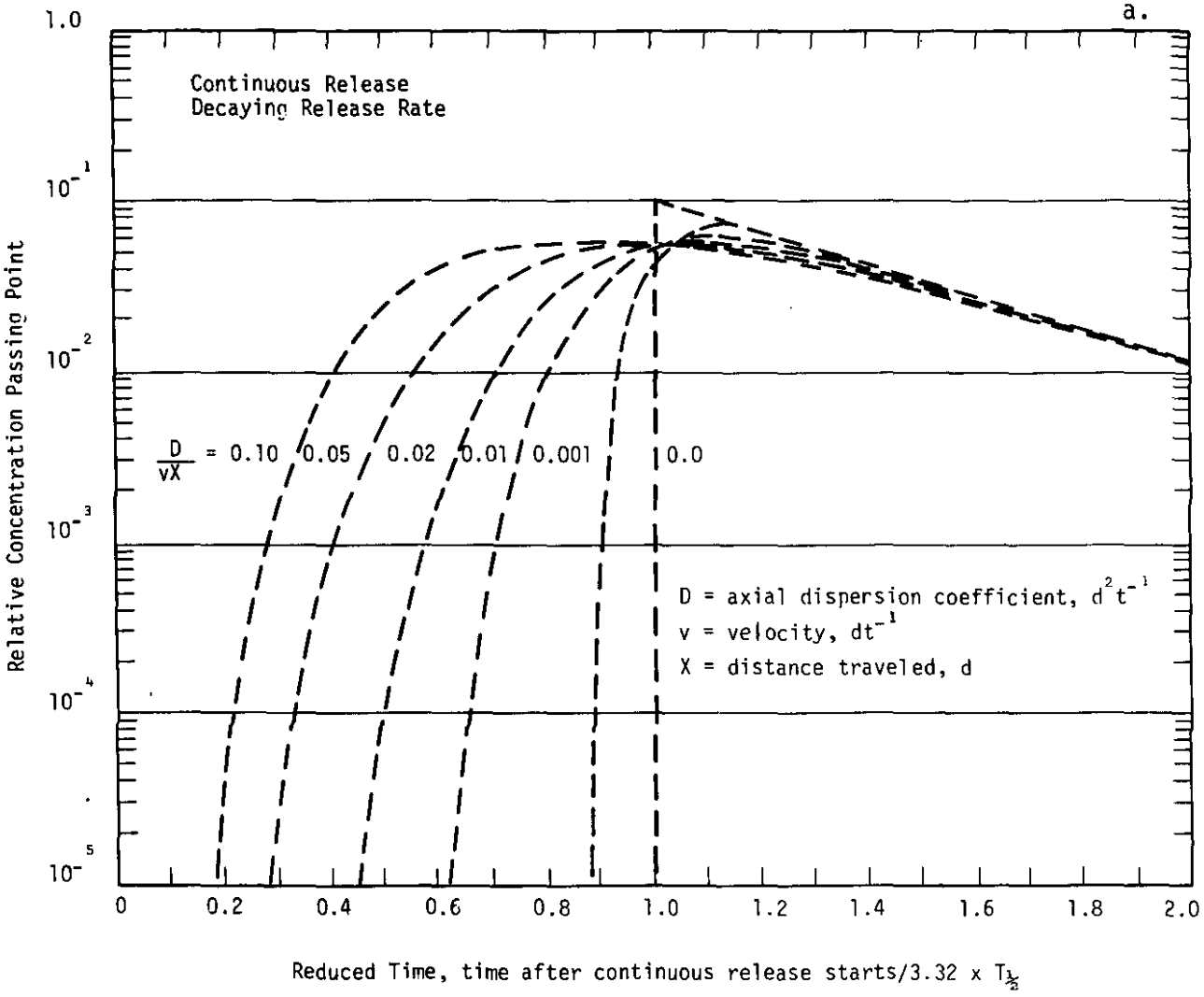

FIGURE 28a. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 3.32 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.10 to zero)

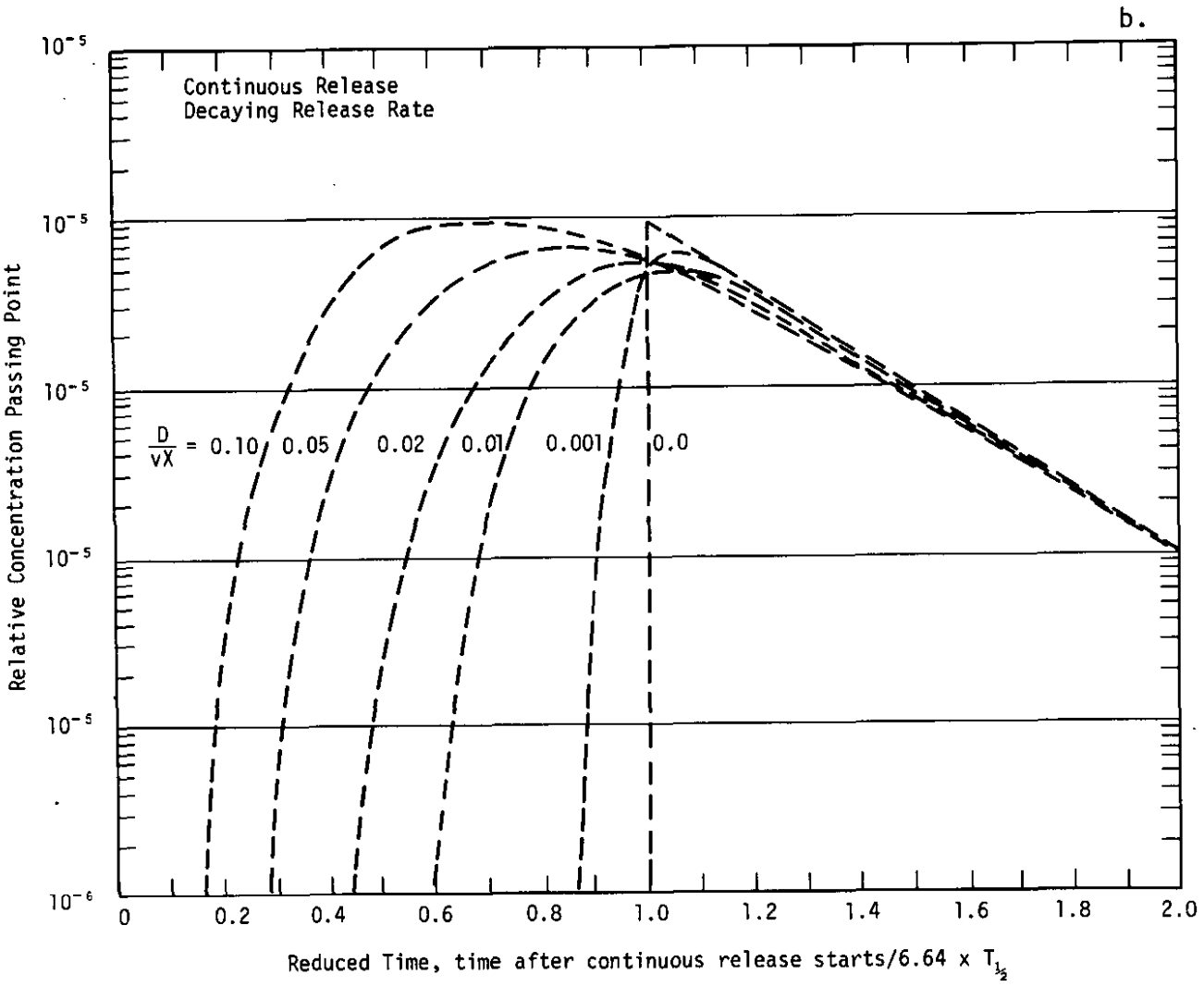

FIGURE 28b. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 6.64 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.10 to zero)

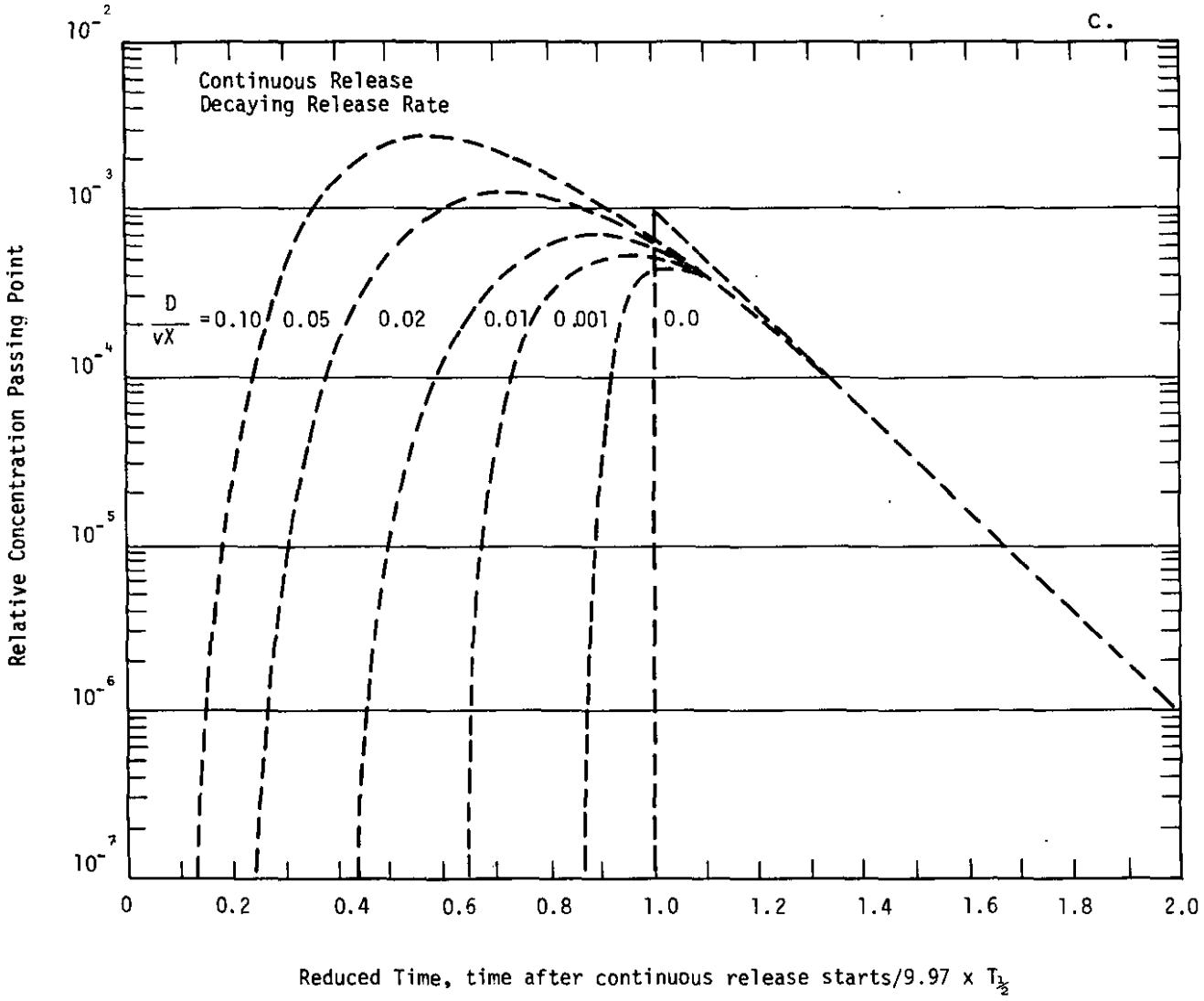

FIGURE 28c. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 9.97 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.10 to zero)

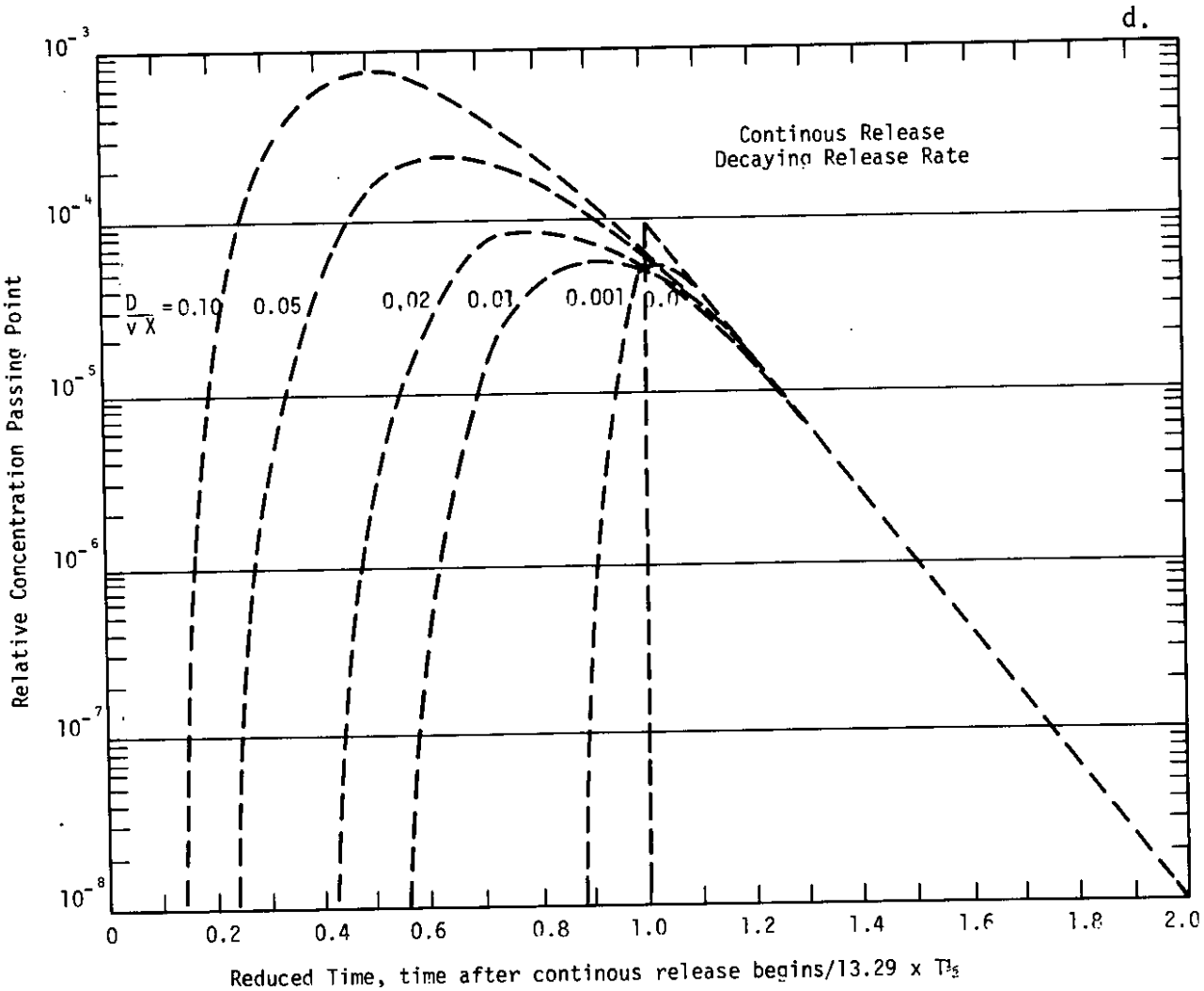

FIGURE 28d. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 13.29 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.10 to zero)

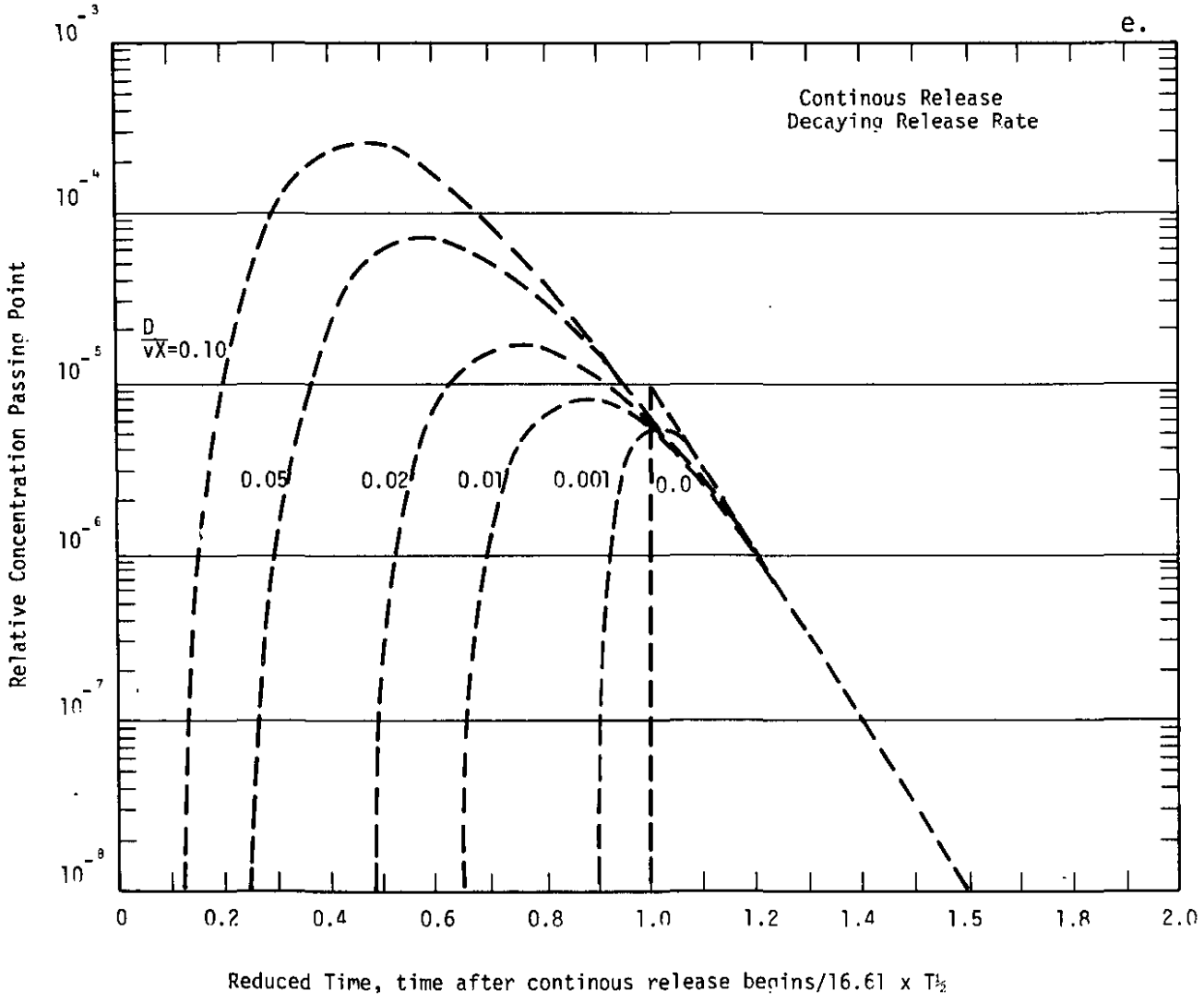

FIGURE 28e. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 16.61 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.10 to zero)

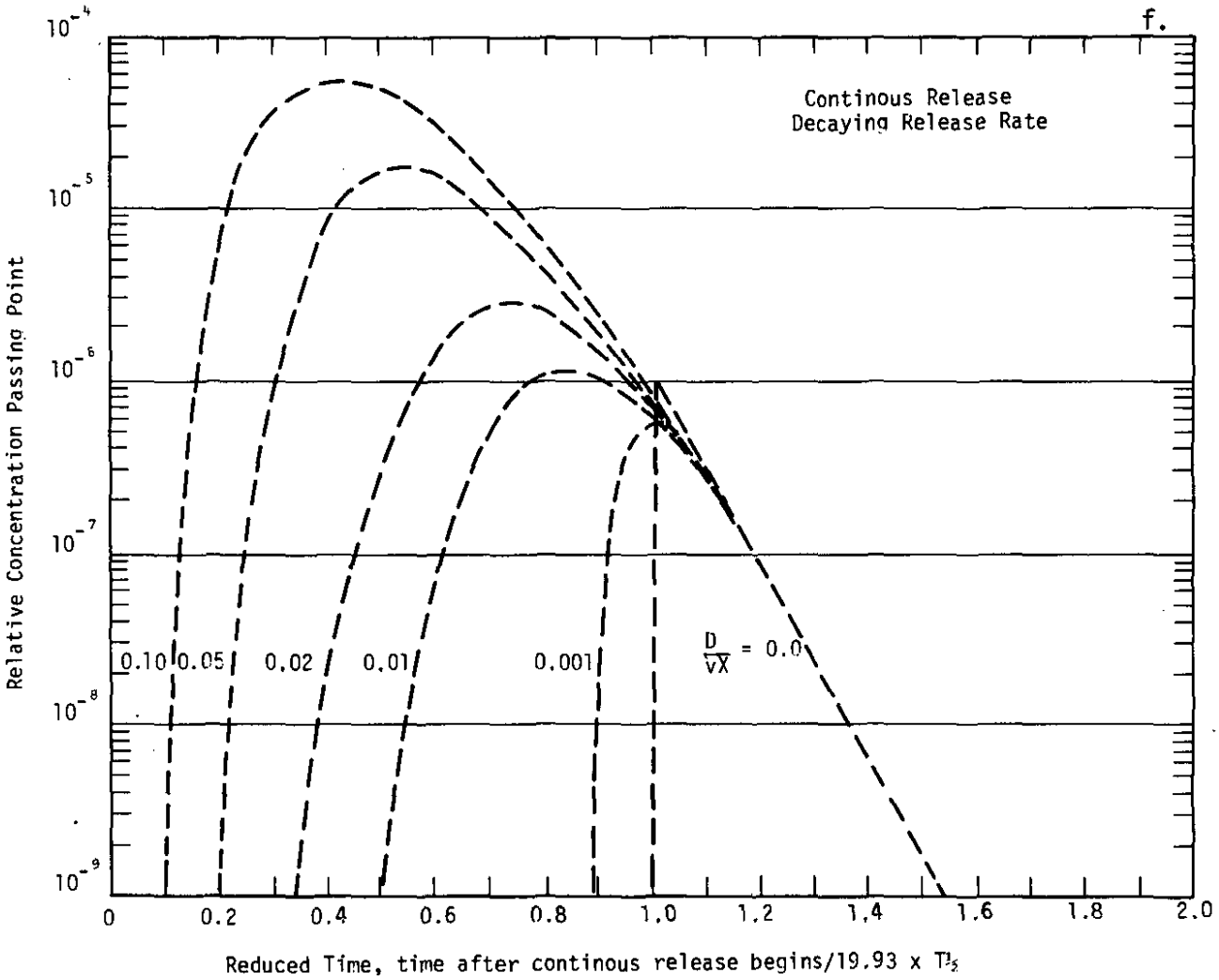

FIGURE 28f. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (time reduction factor of 19.93 x $T_{\frac{1}{2}}$ and dispersion numbers, D/vX, of 0.10 to zero)

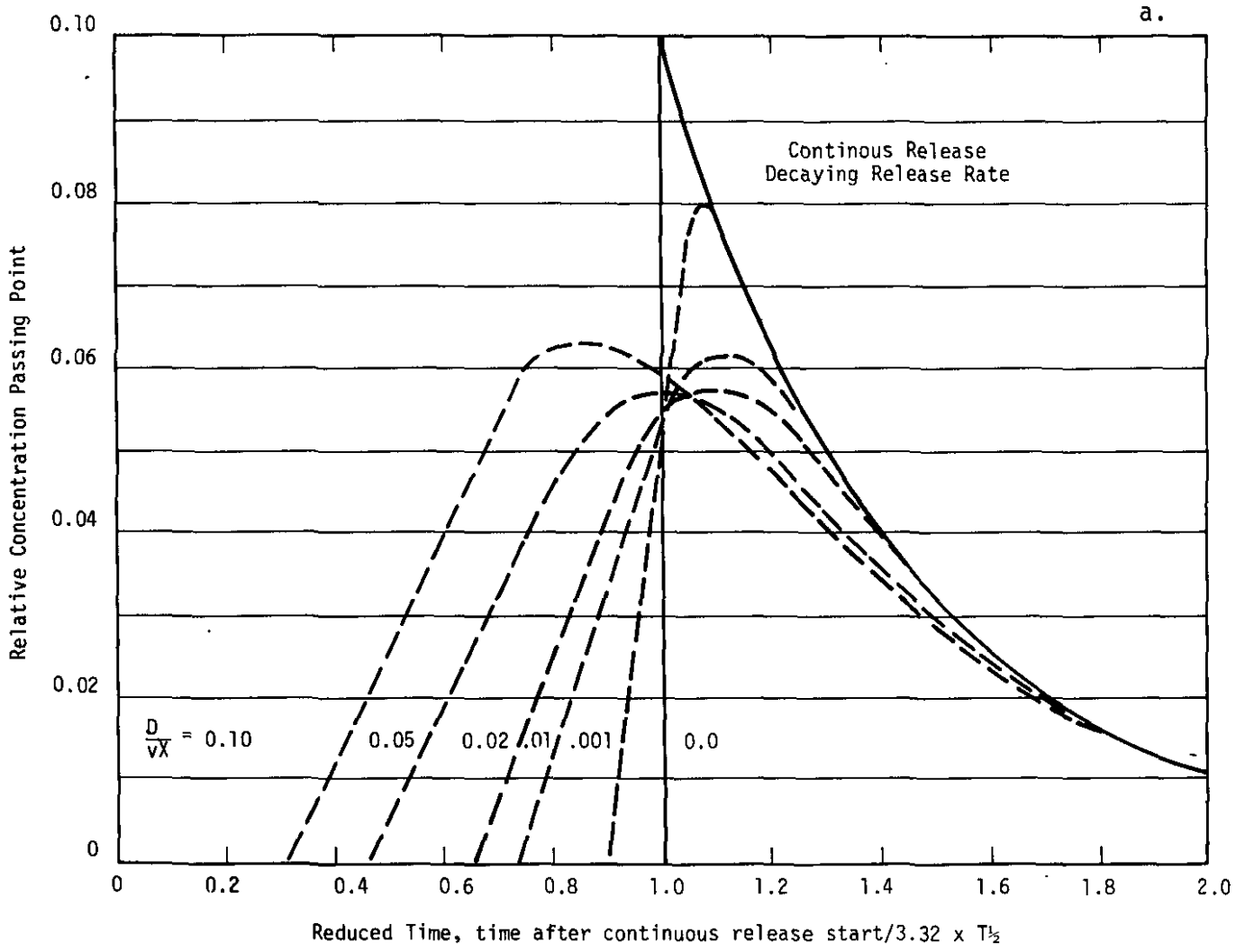

FIGURE 29a. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 28a, except the ordinate is linear rather than logarithmic)

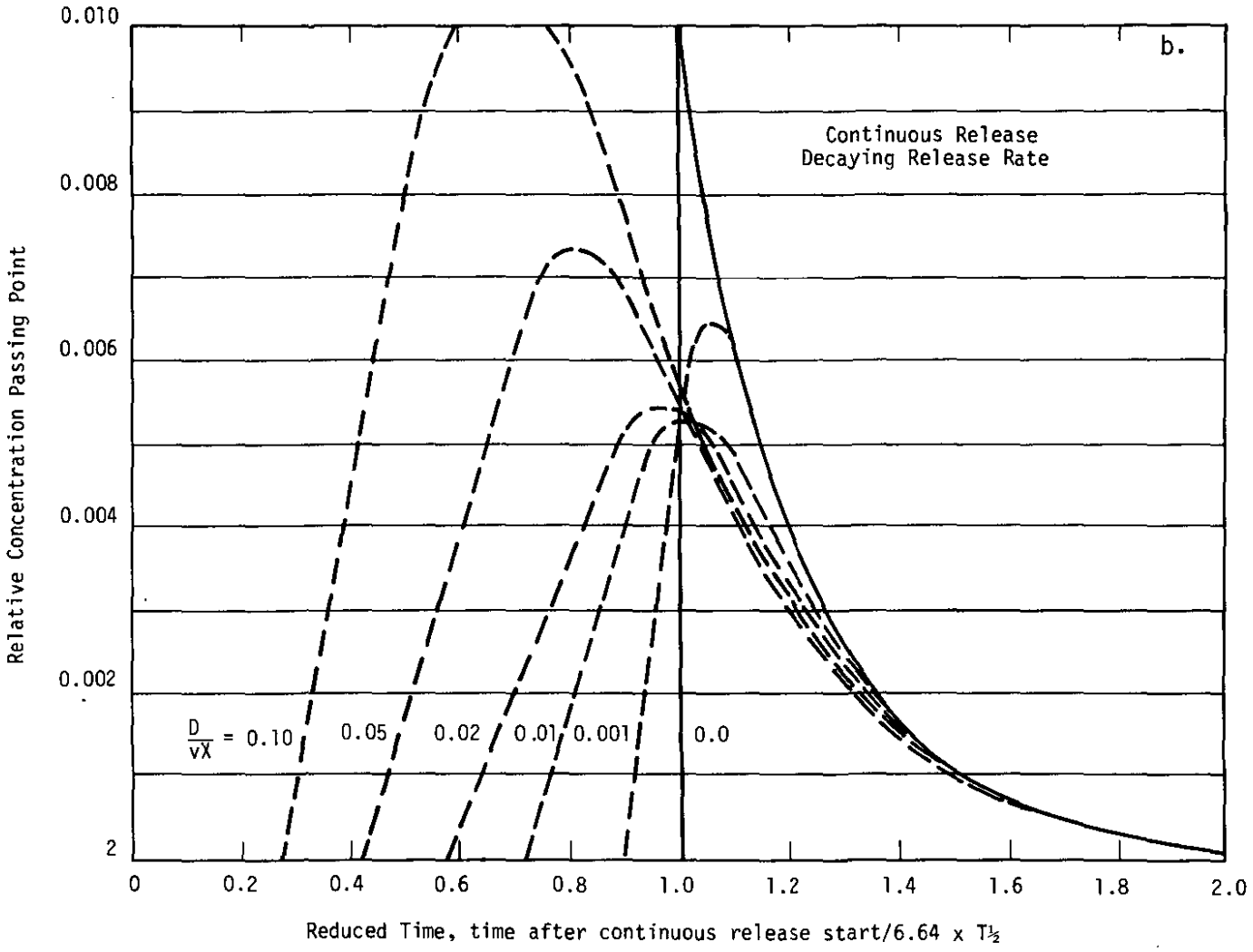

FIGURE 29b. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 28b, except the ordinate is linear rather than logarithmic)

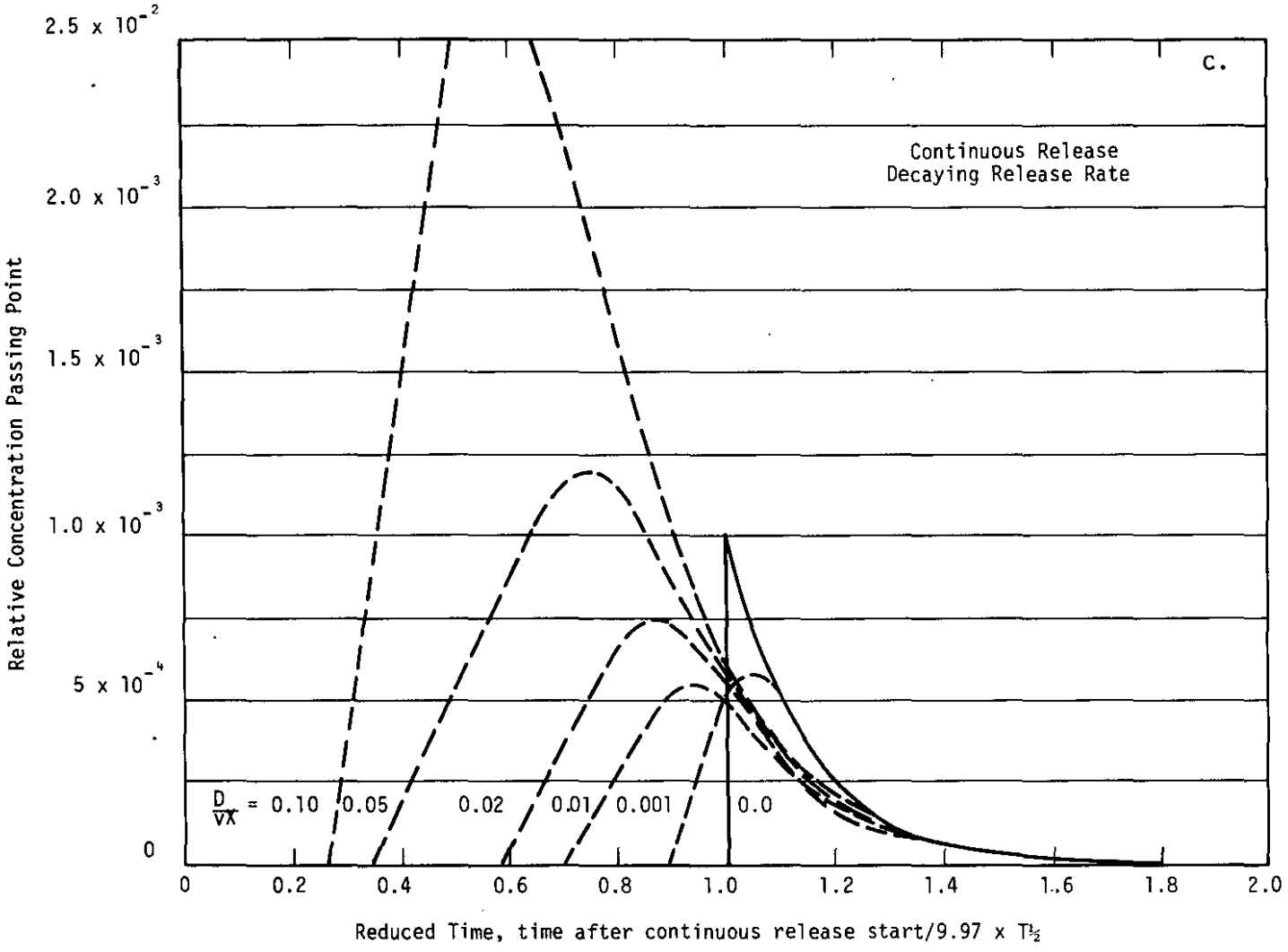

FIGURE 29c. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 28c, except the ordinate is linear rather than logarithmic)

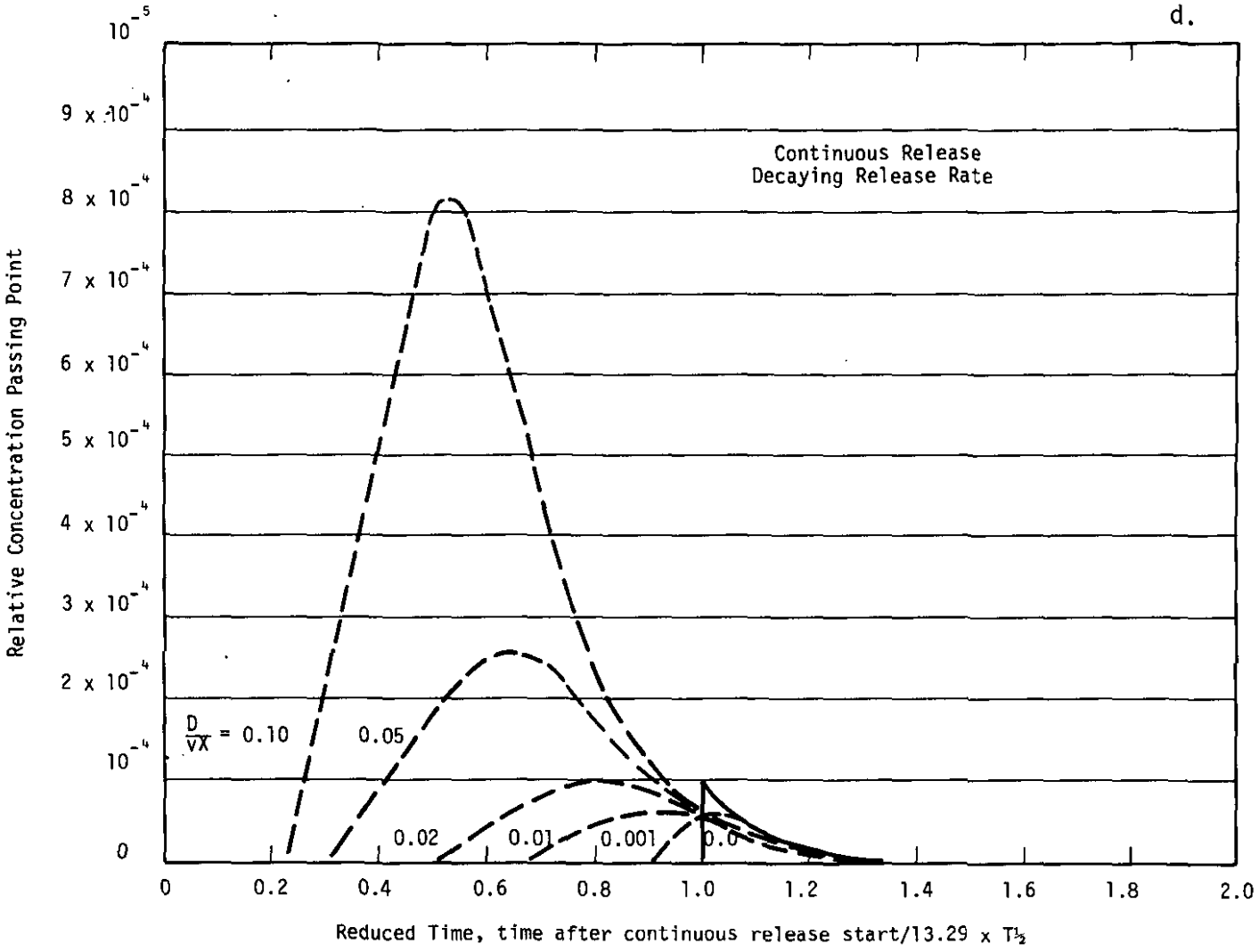

FIGURE 29d. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 28d, except the ordinate is linear rather than logarithmic)

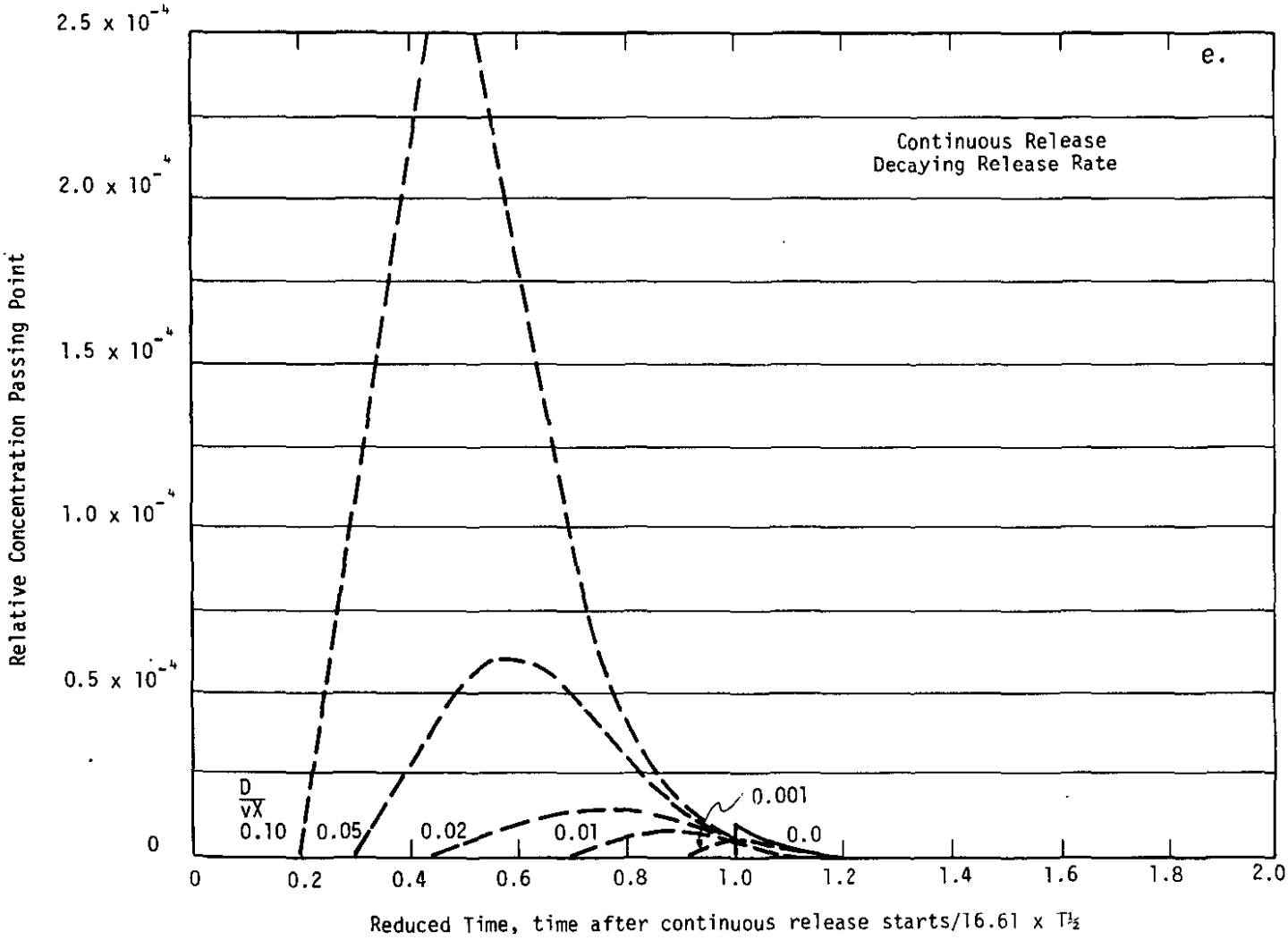

FIGURE 29e. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 28e, except the ordinate is linear rather than logarithmic)

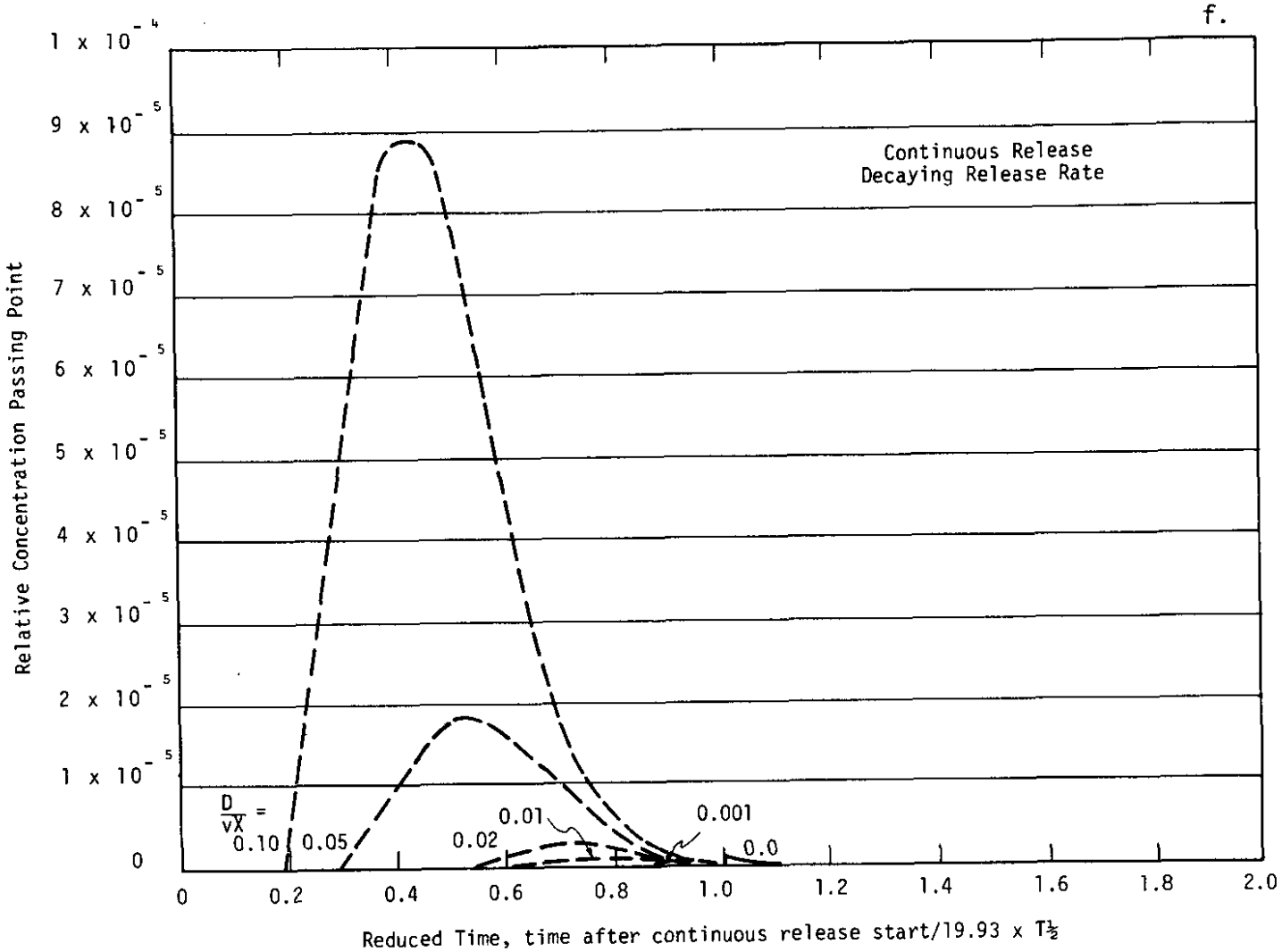

FIGURE 29f. Continuous Release with Decaying Release Rate: Relative Amount of Released Radionuclides Passing a Downstream Point Relative to Initial Concentration (similar to Figure 28f, except the ordinate is linear rather than logarithmic)

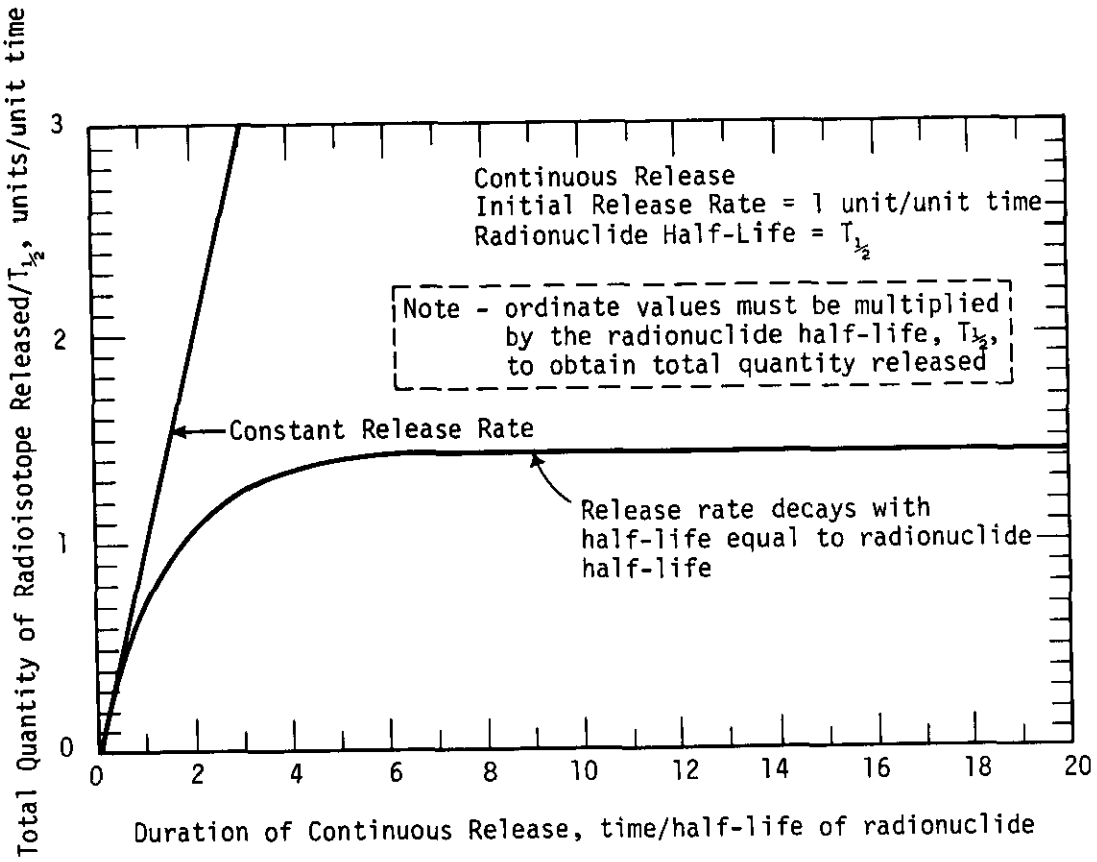

FIGURE 30. Continuous Release: Total Quantity of Radionuclide Released as a Function of the Duration of the Release (constant and decaying release rates)

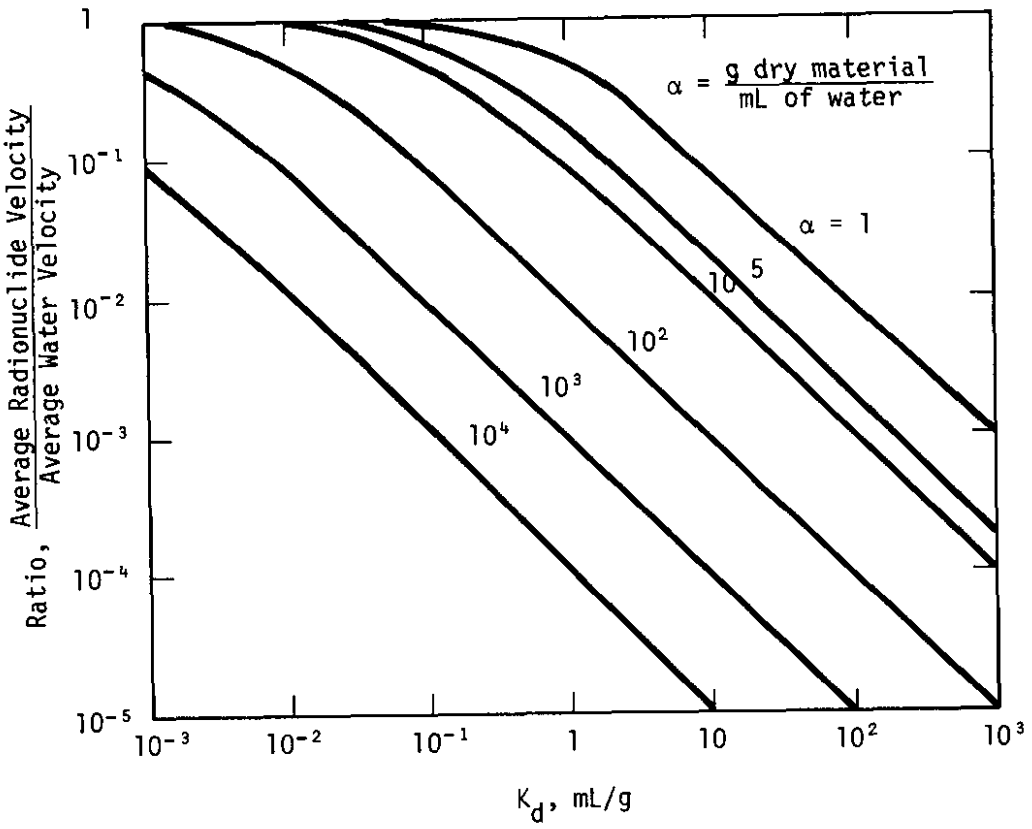

FIGURE 31. Ratio of Radionuclide Velocity to Groundwater Velocity as a Function of the Distribution Coefficient (K_d) and Mass/Volume Ratio (α)

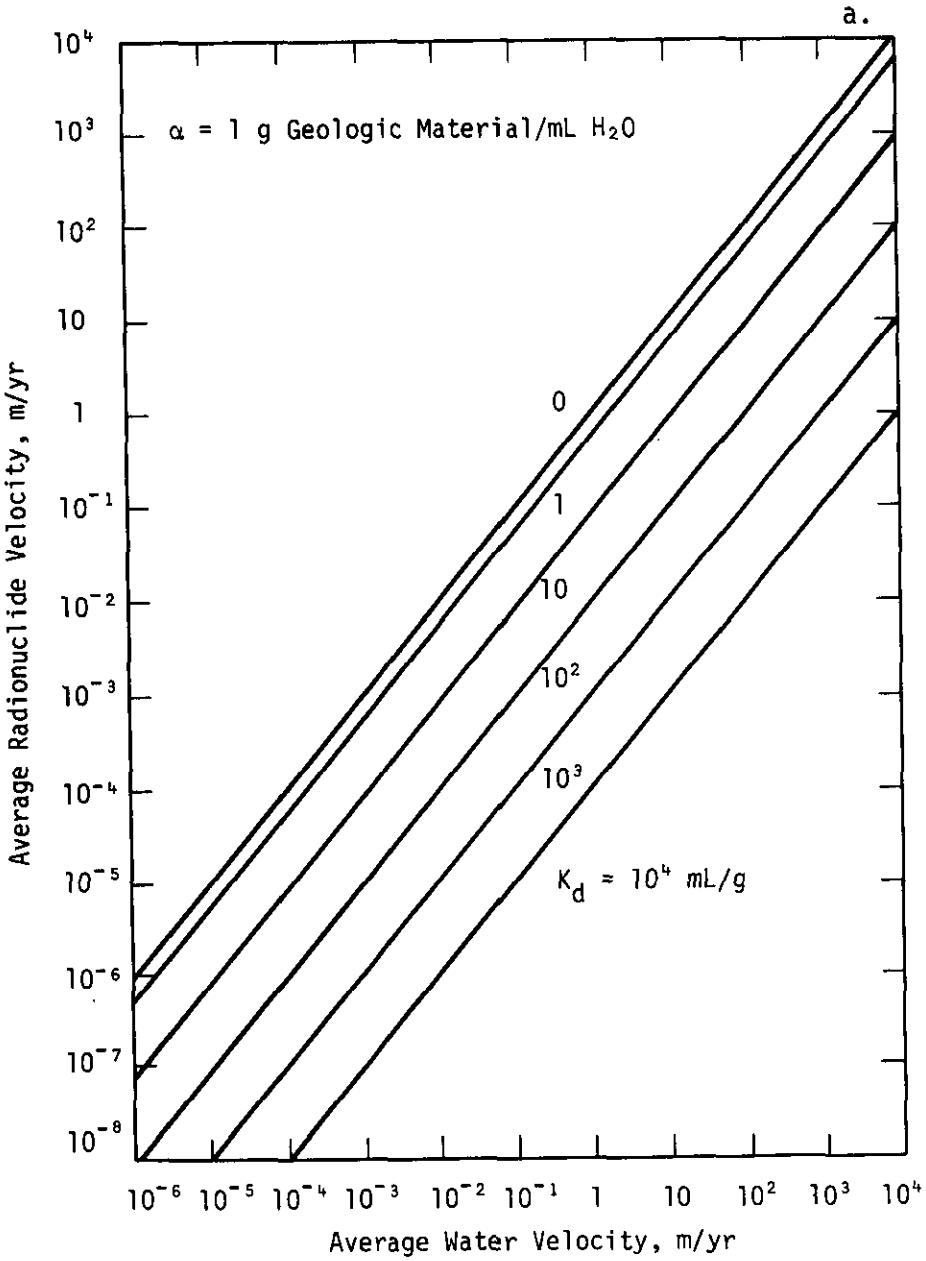

FIGURE 32a. Transport Velocity of Radionuclide versus Groundwater Velocity (for K_d values 0 to 10^4 mL/g and an α value of 1 g/mL)

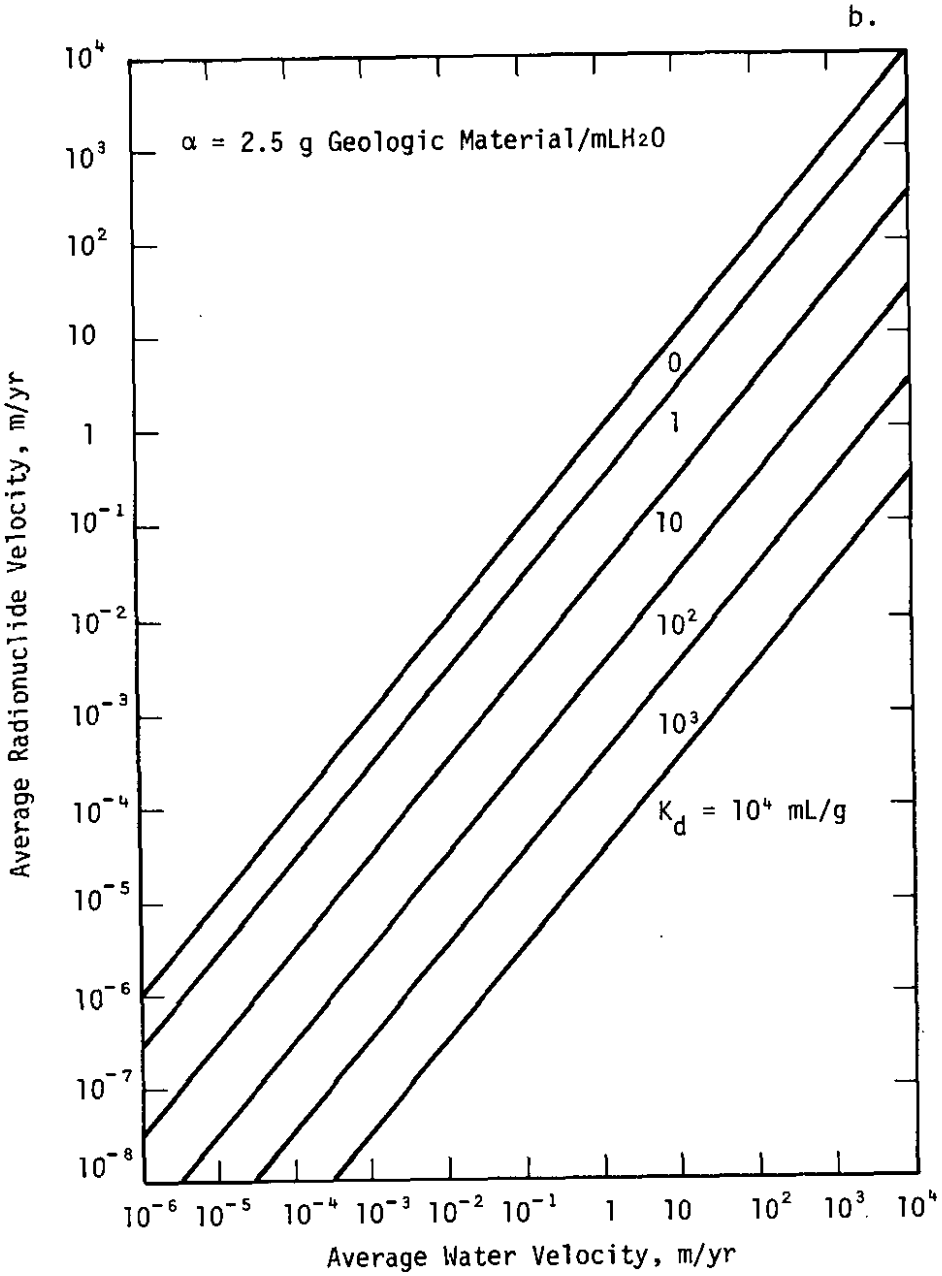

FIGURE 32b. Transport Velocity of Radionuclide versus Groundwater Velocity (for K_d values 0 to 10^4 mL/g and an α value of 2.5 g/mL)

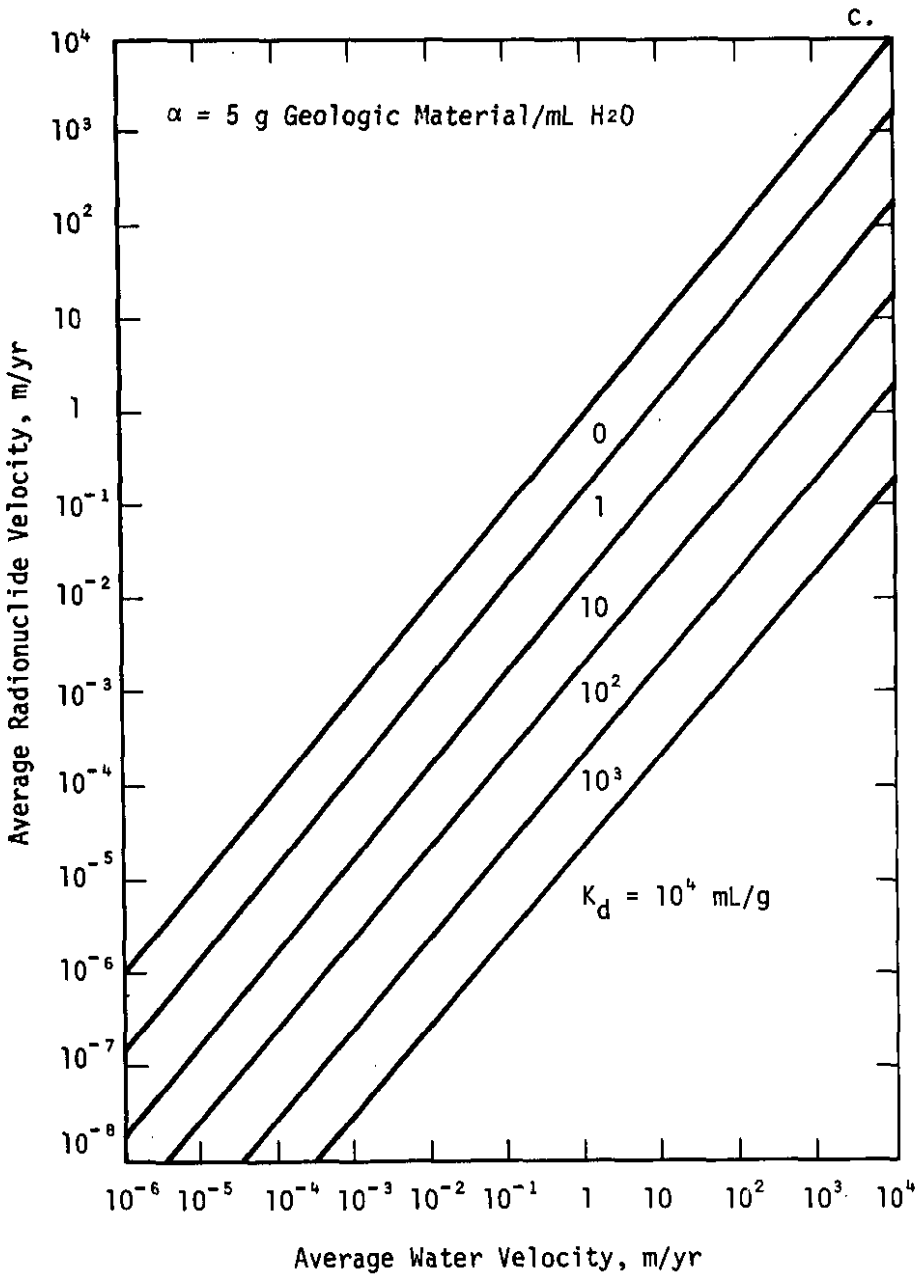

FIGURE 32c. Transport Velocity of Radionuclide versus Groundwater Velocity (for K_d values 0 to 10^4 mL/g and an α value of 5 g/mL)

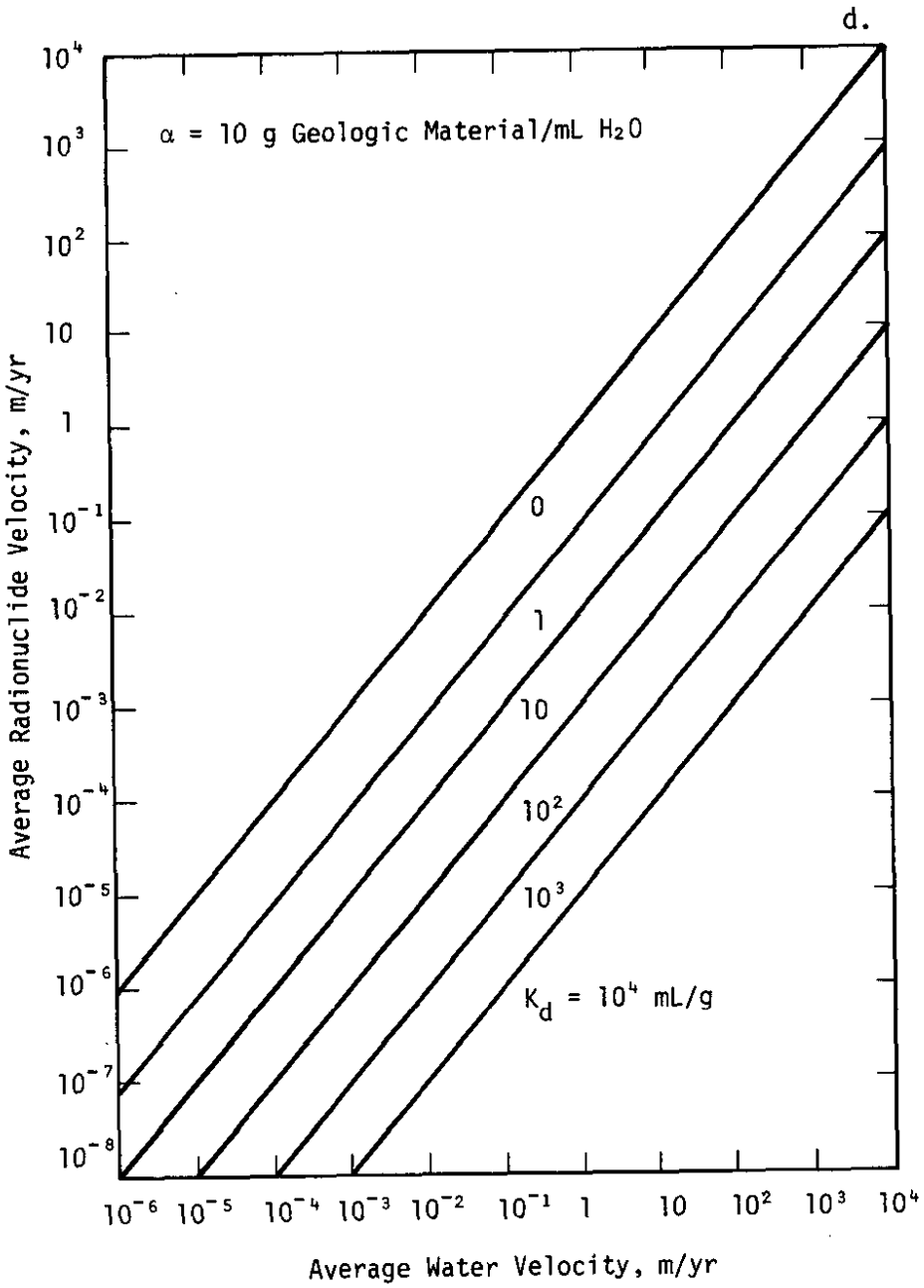

FIGURE 32d. Transport Velocity of Radionuclide versus Groundwater Velocity (for K_d values 0 to 10^4 mL/g and an α value of 10 g/mL)

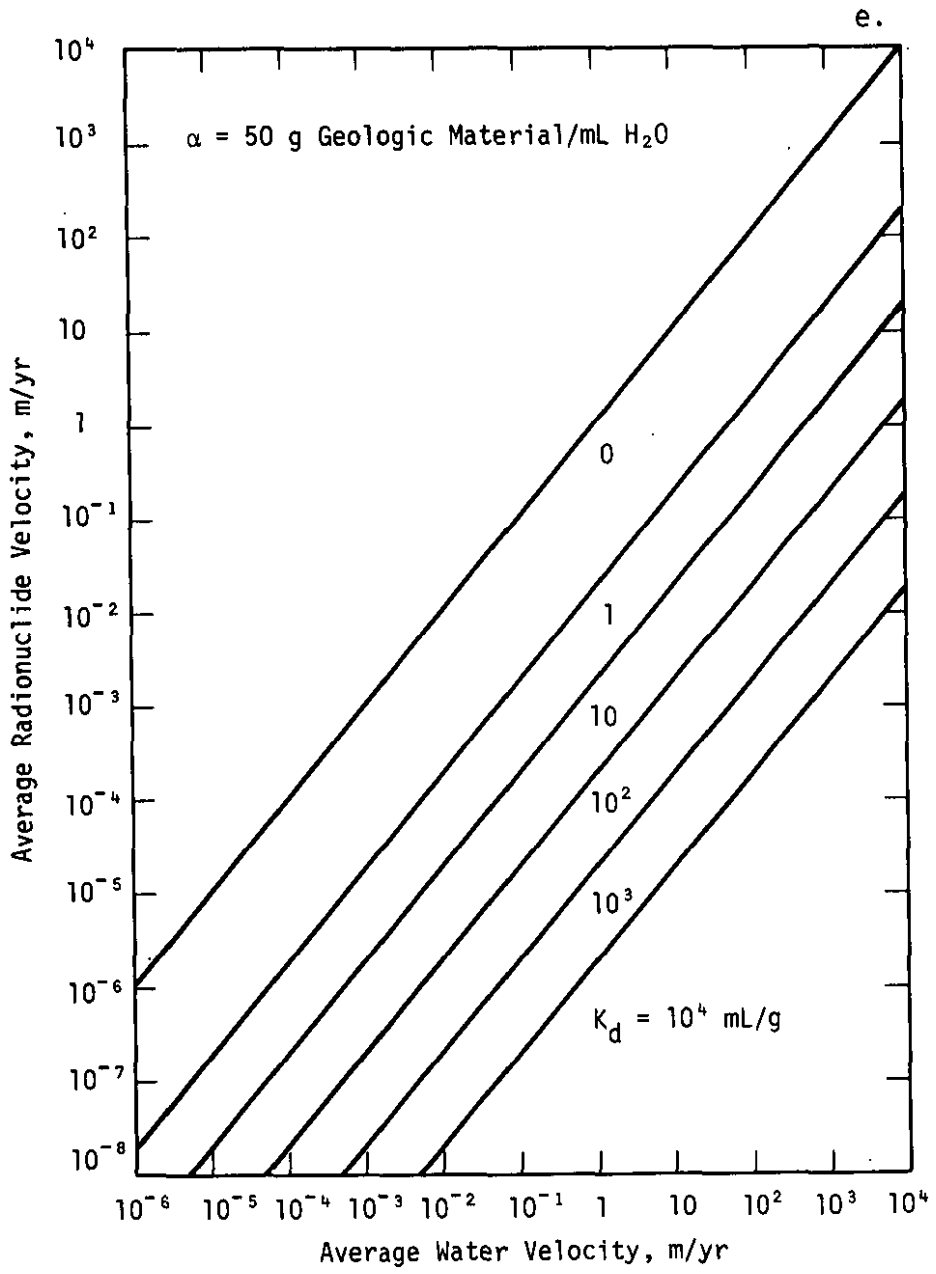

FIGURE 32e. Transport Velocity of Radionuclide versus Groundwater Velocity (for K_d values 0 to 10^4 mL/g and an α value of 50 g/mL0

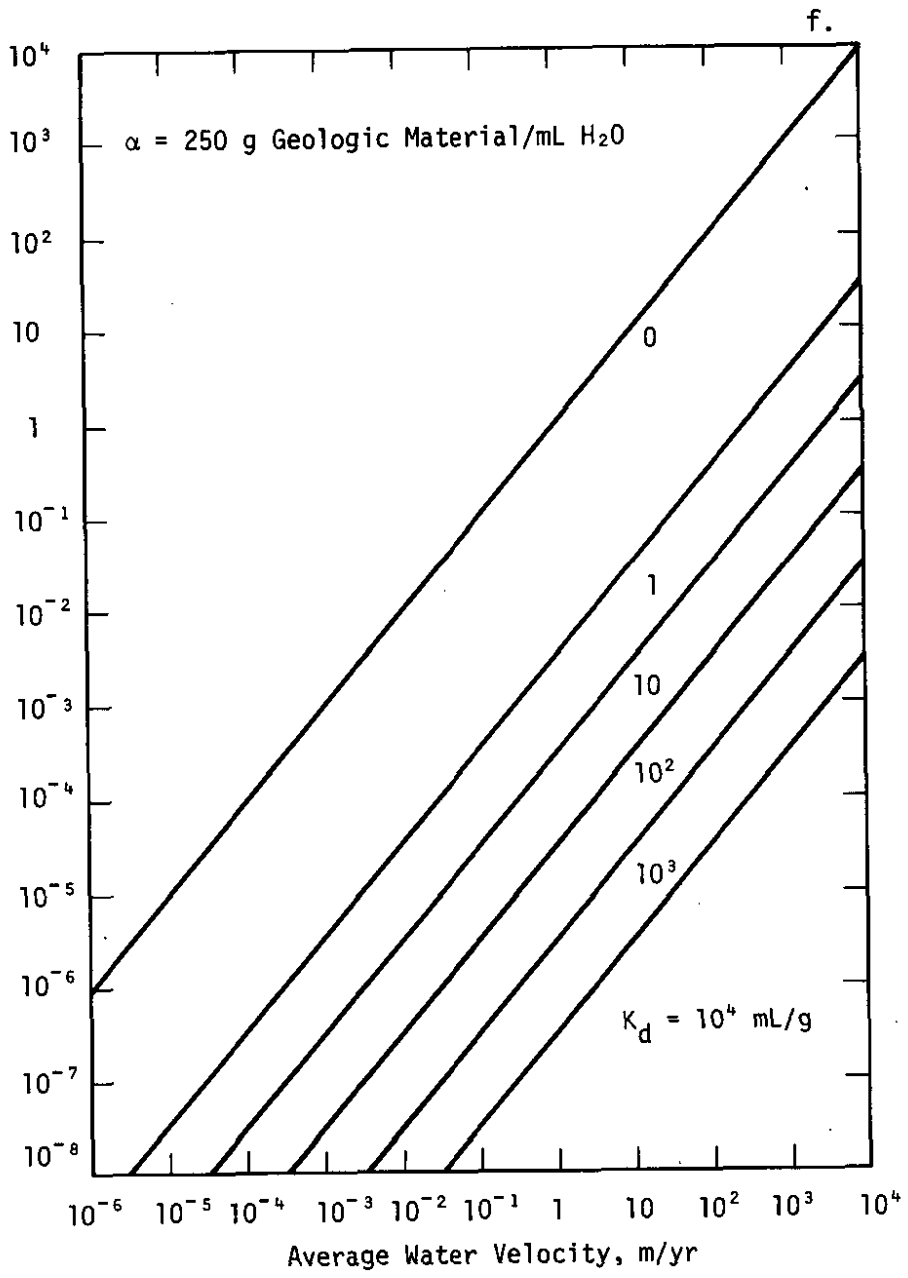

FIGURE 32f. Transport Velocity of Radionuclide versus Groundwater Velocity (for K_d values 0 to 10^4 mL/g and an α value of 250 g/mL)

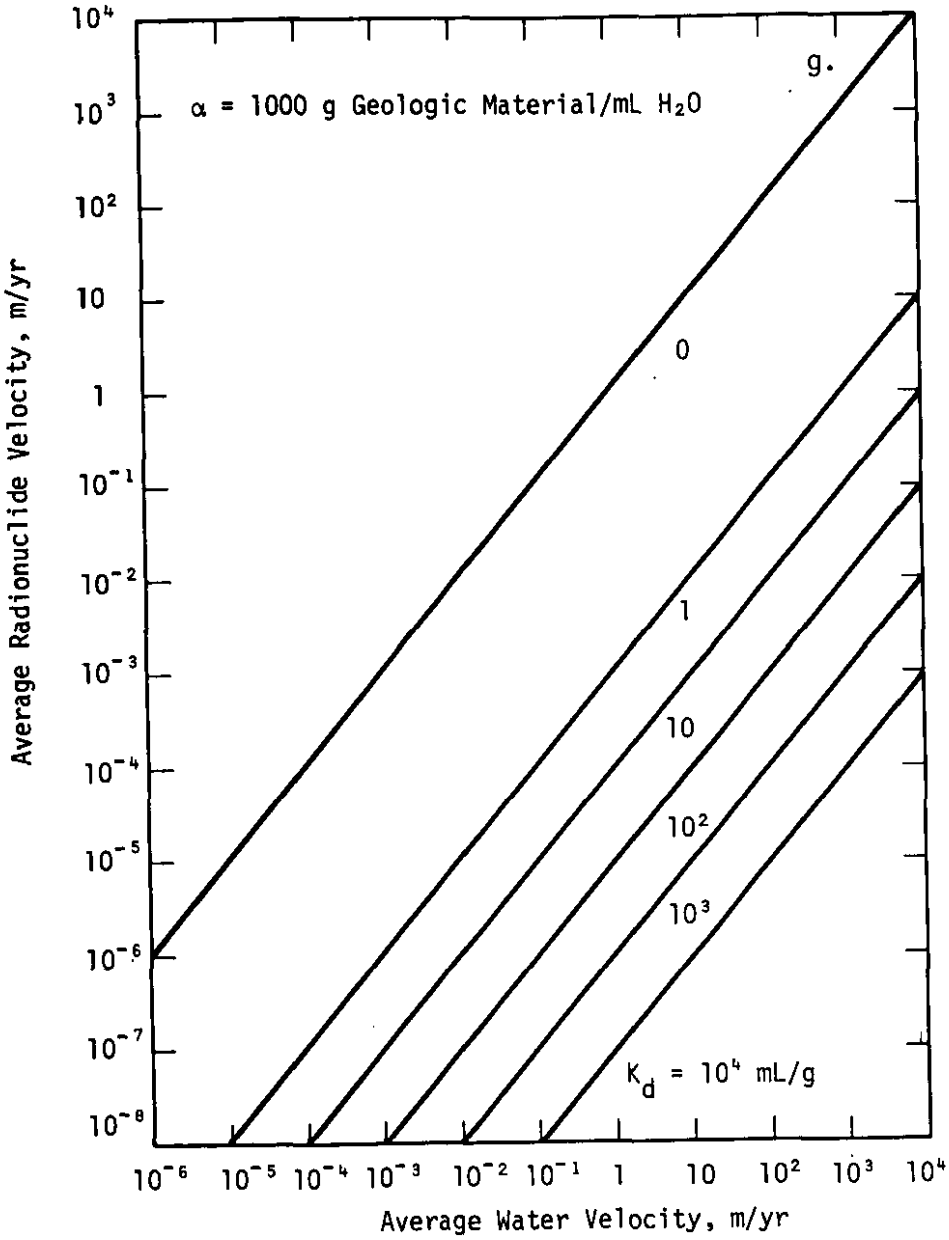

FIGURE 32g. Transport Velocity of Radionuclide versus Groundwater Velocity (for K_d values 0 to 10^4 mL/g and an α value of 1000 g/mL)

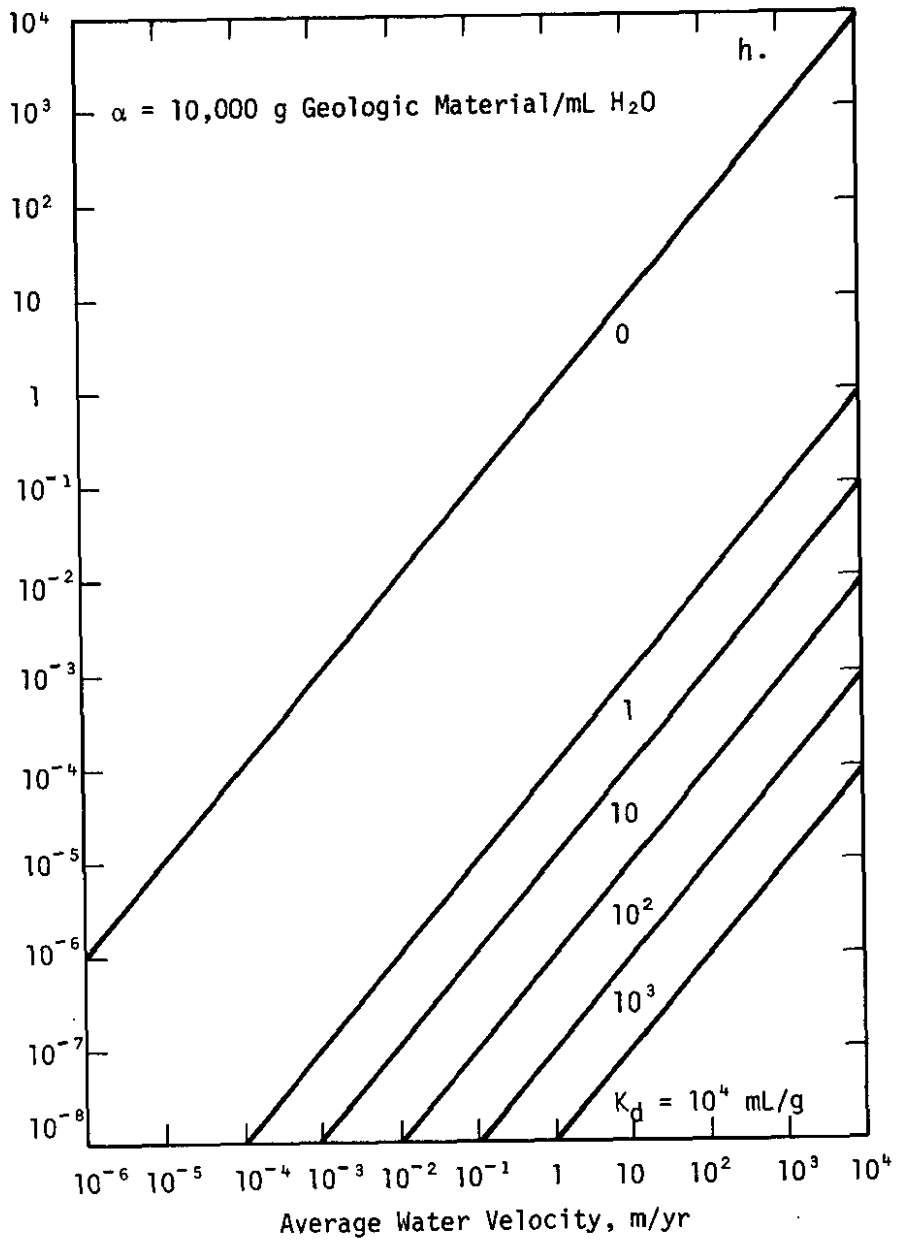

FIGURE 32h. Transport Velocity of Radionuclide versus Groundwater Velocity (for K_d values 0 to 10^4 mL/g and an α value of 10 kg/mL)